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Feasibility of Producing and Marketing Byproduct Gypsum from SO2 Emission Control at Fossil-Fuel-Fired Power Plants

Tennessee Valley Authority, Muscle Shoals, AL

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Feasibility of Producing and Marketing Byproduct Gypsum from SO_2 Emission Control at Fossil-Fuel-Fired Power Plants

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16. ABSTRACT
The report gives results of a study to identify fossil-fuel-fired power plants that might, in competition with existing crude gypsum sources and other power plants lower the cost of compliance with SO2 regulations by producing and marketing abatement gypsum. In the Eastern U.S., gypsum production has a limited but important potential to lower the cost of compliance by power plants. Gypsum consumption was projected as 2 million tons in wallboard use and 3 million tons in cement, and total 1978 sales were estimated at $124.4 million in the Eastern U.S. Potential gypsum production by 113 Eastern U.S. steam plants requiring flue gas desulfurization for compl ance amounts to 27 million tons. For about 90% of the potential abatement gypsum production, the cost difference between producing gypsum and conventional sulfite sludge by limestone scrubbing is greater than the estimated cost of mining natural gypsum. However, 30 power plants (generally <200 MW) with small annual outputs were identified that could reduce compliance cost by producing and marketing abatement gypsum The 30 plants would replace 2.23 million tons of crude gypsum at 93 demand points (92 cement plants and 1 wallboard plant). Of the gypsum replaced, 74% is imported. First-year saving to steam plants is $11 million, and about $2 million is saved by the gypsum industry.

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Byproducts	Flue Gases	Flue Gas Desulfurization	14B	21B
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ABSTRACT

The major purpose of the study was to identify fossil-fired power plants that might, in competition with existing sources of crude gypsum and other power plants, lower cost of compliance with SO_2 regulations by producing and marketing abatement gypsum.

It was estimated that 187 fossil-fired power plants will be out of compliance with existing SO_2 regulations in 1978. Of these, 71 were assumed to use low-sulfur fuel in lieu of a flue gas desulfurization strategy to meet compliance due to extremely high absolute flue gas desulfurization costs. Total first-year costs for the remaining 116 plants to install and operate the limestone slurry flue gas desulfurization system is $2 billion to remove 4 million tons of sulfur. Since only 3 of the 116 plants are located in Western States near gypsum-producing areas, the gypsum production alternative is not considered a viable or important alternative to steam plants in Western States. In the eastern part of the United States, however, gypsum production was shown to have a limited but important potential to lower cost of compliance by power plants. Gypsum consumption was projected to amount to 2 million tons in wallboard use and 3 million tons in cement, and total value of sales in 1978 was estimated at $124.4 million in that region.

Total potential gypsum production by the 113 steam plants in the eastern part of the United States amounts to 27 million tons. For about 90% of the potential abatement gypsum production, the cost difference between producing gypsum and producing conventional sulfite sludge by limestone scrubbing is greater than the estimated cost of mining natural gypsum. Thirty power plants (generally smaller than 200 MW) with small annual outputs were identified that could reduce compliance cost by producing and marketing abatement gypsum. The thirty plants would replace 2,230,000 tons of crude gypsum at 93 demand points (92 cement plants and one wallboard plant). Seventy-four percent of the gypsum replaced is imported material. Total first-year saving to steam plants is $11 million and about $2 million is saved by the gypsum industry. Production of gypsum instead of sludge as a means of compliance with SO_2 regulations was shown to be suited to small, new plants and may well fill an important role in a total program of byproduct marketing by steam plants in meeting compliance.

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ABBREVIATIONS, GLOSSARY, AND GENERAL CONVERSION FACTORS

ABBREVIATIONS

ACFL	Alternative clean fuel level
AQCR	Air Quality Control Regions
EPA	U.S. Environmental Protection Agency
FGD	Flue gas desulfurization
FPC	Federal Power Commission
G[a]	Billion (10^9)
k[a]	Thousand (10^3)
M[a]	Million (10^6)
NAAQS	National Ambient Air Quality Standards
NSPS	New Source Performance Standards
SIP	State Implementation Plans
SMSA	Standard Metropolitan Statistical Areas
T	Trillion (10^{12})
TVA	Tennessee Valley Authority
UOP	Universal Oil Products

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a. Although British units are used in this report, the International System of Units (SI) symbols are used in transition to the metric system.

GLOSSARY

Alternative clean fuel level: The value assigned to premium price for fuel that will meet the sulfur oxide emission standard.

Anhydrite: Anhydrous calcium sulfate ($CaSO_4$).

Capacity factor: Throughout this study capacity factor is defined and calculated as the ratio of the annual quantity of heat consumed in the boiler in comparison to the quantity that would have been consumed if the boiler operated at rated capacity (full load) for the entire year (8760 hr). For steam electric boilers, this definition is equal to capacity factors calculated in terms of either steam or electricity generation.

Chiyoda process: A process developed by Chiyoda Engineering Company in Japan to remove sulfur oxide from flue gas, oxidize the sulfur oxide to produce dilute sulfuric acid, and react the acid with limestone to produce gypsum.

Competitive equilibrium solution: Represented by the long-run break-even market condition which comes at a critical price where identical firms just cover their full competitive costs. At a lower long-run price, firms would leave the industry until prices return to the critical equilibrium level; at higher long-run price, new firms would enter the industry replicating what existing firms are doing and thereby force market price back down to the long-run equilibrium price where all competitive costs are just covered.

Dowa process: A process developed by Dowa Mining Company in Japan to remove sulfur oxide from flue gas by scrubbing with aluminum sulfate solution, oxidizing the absorbed sulfur dioxide, and regenerating the absorber solution by adding limestone to precipitate gypsum.

Form 67: Federal Power Commission form used to report annual steam-electric plant and water quality control data.

Gypsite: Impure gypsum (less than 70% $CaSO_4 \cdot 2H_2O$).

Gypsum: $CaSO_4 \cdot 2H_2O$.

Limestone-gypsum process: A process for removing sulfur oxides from flue gas and converting the waste product to calcium sulfate by forced oxidation.

Limestone slurry scrubbing: A process for removing sulfur oxides from flue gases by scrubbing the gases in a tower with a limestone slurry. The resulting slurry of calcium sulfites, sulfates, unreacted limestone, etc., is sent to a disposal pond where the solids settle out with no further treatment.

Market demand: Amount of goods that buyers are ready to buy at each specified price in a given market at a given time (also called demand schedule).

Market supply: Amount of goods that sellers are ready to sell at each specified price in a given market at a given time (also called a supply schedule).

Phosphogypsum: Gypsum byproduct of phosphoric acid production.

GENERAL CONVERSION FACTORS

EPA policy is to express all measurements in Agency documents in metric units. Values in this report are given in British units for the convenience of engineers and other scientists accustomed to using the British system. The following conversion factors may be used to provide metric equivalents.

Conversion Factors for Metric Equivalents of British Units

British			Metric	
ac	acre	0.405	hectare	ha
bbl	barrels of oil	158.97	liters	l
Btu	British thermal unit	252		
ft^3	cubic feet	0.02832	cubic meters	m^3
gal	gallons	3.785	liters	l
lb	pounds	0.4536	kilograms	kg
lb/ft^3	pounds per cubic foot	16.02	kilograms per cubic meter	kg/m^3
lb/hr	pounds per hour	0.126	grams per second	g/sec
ton	tons (short)	0.90718	metric tons	t
ton/hr	tons per hour	0.252	kilograms per second	kg/sec

FEASIBILITY OF PRODUCING AND MARKETING BYPRODUCT GYPSUM FROM SO_2 EMISSION CONTROL AT FOSSIL-FUEL-FIRED POWER PLANTS

EXECUTIVE SUMMARY

The passage of the Clean Air Act in 1967 and the various amendments have prompted increased efforts by government and industry to reduce pollutants in emissions from fossil-fired power plants. Stack gas scrubbing processes for removal of SO_2 emissions have received the most attention. There are alternative systems of scrubbing for removal of SO_2 emissions; but the lime-limestone systems which absorb the SO_2 and convert it to solid compounds of calcium sulfites and sulfates, which are then discarded, have been most widely applied by the industry. Those processes are called "throwaway" processes. In general, they are less expensive to install and operate than alternative scrubbing systems. However, the throwaway product has no economic value, is costly to discard, may create future problems of ground water pollution, and wastes sulfur, a vital resource.

Processes recovering the SO_2 in useful form are potentially superior to the lime-limestone methods because they overcome the disadvantages associated with the wastes from throwaway systems. Before such systems will be put into use, however, there must be confidence that the useful byproduct will generate adequate sales revenue to offset additional cost, if any, of the alternative systems. The U.S. Environmental Protection Agency (EPA) and the Tennessee Valley Authority (TVA) have conducted studies to evaluate the feasibility of marketing byproducts from SO_2 emission control. The design of the system(s) chosen was developed from available data, costs were estimated on a uniform basis, and potential markets were determined for the byproducts.

A major purpose of this study was to evaluate the existing wallboard products industry and cement industry as markets for abatement gypsum produced by an SO_2 emission control system. Gypsum-producing systems are in use on oil-fired boilers in Japan and the resultant product is used successfully in wallboard manufacturing. Samples of gypsum from a pilot operation on a coal-fired facility in Florida have been successfully used in wallboard manufacturing under commercial conditions.

The wallboard products manufacturing industry is currently the dominant user of gypsum. This market potential has been given major attention, but consideration has also been given to potential uses in the cement industry. The major objectives of the study were:

1. To identify basic conditions of supply and demand for the gypsum industry.
2. To characterize demand and projected growth in demand by major markets.
3. To identify potential problems in market entry and to suggest market strategies.
4. To evaluate costs for several different gypsum-producing flue gas desulfurization (FGD) systems and to develop cost estimates for representative systems.
5. To further develop and improve an analytical model for conducting abatement product marketing investigations.
6. To apply the model to determine optimum strategies for the industry on a plant-by-plant basis and in total.
7. To suggest further research needs.

The study was approached in four sequential steps. The existing gypsum industry was analyzed first to determine the market potential for abatement gypsum. Specific quantities and costs were developed for each demand point and for the total industry. Next, the cost of SO_2 emission control by gypsum-producing processes was compared with the limestone throwaway system to determine a basis for the supply of abatement gypsum from which the total potential production and costs were calculated. Then the revenue based on the replacement of crude gypsum was determined and compared with calculated production costs. Specific plants were identified that have an economic incentive to control SO_2 emissions by gypsum production. Results, conclusions, and limitations were summarized in the final step.

MAJOR ASSUMPTIONS

The study was conducted under the premise that all steam plants must operate in compliance with existing SO_2 regulations. It was assumed that use of low-sulfur fuel is an available alternative to meet compliance. A premium (incremental) cost of $0.70/MBtu (M = 1 million) heat input was assumed for complying fuel. Determination of actual premium value was beyond the scope of the study; the level chosen is a reasonable economic screen. Boilers were not considered to be candidates to install an FGD system when calculated cost of scrubbing exceeded $0.70/MBtu heat input. All remaining boilers were assumed to install the limestone throwaway system unless revenue from sale of abatement gypsum was adequate to offset or exceed the additional cost of the gypsum-producing SO_2 emission control system. Abatement gypsum was assumed to be interchangeable with natural gypsum in the manufacture of wallboard and cement. Revenue generated from sales of abatement gypsum was based on a projected quantity and delivered cost of crude gypsum to each currently existing demand point. Any demand point was assumed to purchase abatement gypsum if cost was equal to or less than estimated current delivered cost of crude gypsum. The study focused on supply to users of gypsum and not on markets for the end products.

THE GYPSUM INDUSTRY

Gypsum is a naturally occuring nonmetallic mineral found in almost limitless deposits in many parts of the world. Reserves exist in many sections of the United States with the notable exception of coastal areas and the Southeast. Crude gypsum consumed in the areas without natural reserves is mostly imported from Canada. Imports historically account for 35-40% of our domestic needs.

Gypsum is a low-value product since mining costs are low. Variable costs of mining were estimated for purposes of this study at \$3/ton for domestic mines and \$2/ton in Canada. The costs are estimated to be lower in Canada because the quality of reserves is generally better than in the United States. Mining costs vary among regions and by type of mining method used, however, differences could not be quantified.

Domestic gypsum consumption is highly variable and follows the fortunes of the building industry. The year 1973 was a record for the gypsum industry in the United States when consumption amounted to over 20 Mtons. Domestic production was 13,558 ktons (k = 1 thousand) with an average reported mine value of \$4.18/ton (see "Gypsum" by Avery H. Reed, in 1973 Minerals Yearbook, Vol. I, Metals, Minerals, and Fuels, pp. 593-599, published by the U.S. Bureau of Mines, U.S. Department of Interior, U.S. Government Printing Office, Washington, D.C., 1975). Imports amounted to 7,661 ktons with an average reported mine value of \$2.30/ton. Three major markets exist for crude gypsum: (1) the wallboard products industry, 73%; (2) the cement industry, 20%; and (3) agriculture, 7%. According to long-range projections made by the U.S. Bureau of Mines, gypsum use is expected to grow at an annual rate of 1.5-2.0%. Growth is expected in each of the major markets. In addition, the mobile home industry may develop into a new market for wallboard as a result of recent changes in Federal and local building codes.

The wallboard products portion of the industry is both highly concentrated and highly integrated from mining through wallboard manufacture. Entry barriers, now rated high, could be lowered if abatement gypsum does become available. Entry barriers are high partly because the firm controls reserves as well as manufacturing plants. In areas where reserves are not available, the firm normally owns or contracts foreign reserves and attendant facilities to enable ocean transport at minimum cost. If abatement gypsum were available, the wallboard plant would be the only capital investment required to enter the industry.

Most of the gypsum used in the cement industry is purchased from the open market rather than being supplied from captive mines. Cement plants are widely scattered and shipping costs add significantly to delivered costs. Therefore, the logistics and market entry conditions would favor sales of byproducts to the cement industry.

Data bases were developed for the wallboard products industry and the cement industry. The data bases include an estimate of projected gypsum use in 1978 at each wallboard plant and each cement plant based on use in 1973 (the year of maximum consumption). The data bases also include estimated minimum delivered cost of crude gypsum to each demand point. Delivered costs to wallboard plants were based on estimated variable mining cost of \$3/ton f.o.b. domestic mine or \$2/ton f.o.b. foreign mine. In each case, the company-owned mine was considered the supply point for the wallboard plant. The price to the cement industry was based on the current value of crude gypsum used in the cement industry estimated at \$6/ton f.o.b. mine. The two-price system was used because gypsum for wallboard product plants is supplied from captive mines at a lower cost than gypsum for cement.

There was little precedent to draw upon to predict how present crude gypsum producers would react in pricing their product to compete with abatement gypsum. All wallboard producers own or contract their own supplies of crude gypsum. These producers also supply gypsum requirements of the cement industry in an open market.

It was assumed that the integrated producers would continue to mine and distribute crude gypsum to their wallboard plants as long as they met variable cost of mining as estimated above. Since gypsum sales to the cement industry are made in an open market, gypsum producers would be reluctant to lower existing market prices on all crude gypsum sales to compete with localized production of abatement gypsum. For these reasons, the two-price system was used in the major portion of the analysis. Other price situations were also evaluated and reported.

This data base provides total tonnage and revenue potential for abatement gypsum in existing markets. Only three steam plants in the Western United States were found to be candidates to install an FGD system. These three plants are located near gypsum-producing areas. For practical purposes, therefore, the gypsum-producing alternative is not a viable or important alternative for steam plants in the West. The analysis that follows is limited to the Eastern United States.

Projected consumption in 1978 in the Eastern United States is 15 Mtons. Located in this area are 55 wallboard plants and 132 cement plants. Wallboard plants will consume about 12 Mtons and cement plants about 3 Mtons.

Total imports will amount to 5.9 Mtons. Wallboard plants will consume 4.8 Mtons and cement plants will consume 1.1 Mtons of imported material. The total delivered cost of gypsum to demand points in 1978 was estimated at $124,400k with an average value per ton of $8.27. This represents the maximum revenue potential to the utility industry from sales of abatement gypsum in 1978.

FGD COST COMPARISONS

Three gypsum-producing FGD systems--limestone-gypsum, Chiyoda Thoroughbred 101, and Dowa aluminum sulfate--were chosen to be evaluated in this study. In addition, costs for the limestone slurry throwaway system originally developed by TVA were updated to the same base conditions. A brief description of each process follows:

1. Limestone slurry process. Downstream of an electrostatic precipitator (ESP) which is used for particulate removal, stack gas is washed in a mobile-bed absorber with a recirculating slurry of limestone and reacted calcium salts to remove SO_2. Limestone feed is wet ground prior to addition to the absorber effluent hold tank. Calcium sulfite and sulfate salts are withdrawn to a disposal area for discard. Cleaned gas from the absorber is reheated to 175°F before exiting the stack. Design is based on data taken from the EPA-TVA-Bechtel Shawnee test program.

2. Limestone-gypsum process. Particulate and SO_2 removal is accomplished in the same manner as in the limestone slurry process. A bleedstream from the absorber is fed to a neutralization reactor where it is contacted with 98% sulfuric acid to convert excess calcium carbonate in the slurry to gypsum and to lower the pH of the stream to approximately 4.0-4.5 to facilitate downstream oxidation. The reaction product is fed to a high-pressure oxidizer where calcium sulfite in the slurry is contacted with air to form gypsum. The gypsum product is dewatered by thickener and belt filter and conveyed to a storage area. The process (based on Japanese technology) is a conceptual design developed by TVA to be used for comparison with other gypsum-producing processes.

3. Chiyoda 101 process. After particulate removal in an ESP, gas is contacted with a dilute (2-3%) sulfuric acid solution in a specially designed absorber-oxidizer vessel to convert SO_2 to sulfuric acid. Rich liquor is withdrawn from the absorber and reacted with a limestone slurry in a Chiyoda-designed crystallizer to form gypsum. Limestone feed is wet ground prior to addition to the crystallizer. Overflow from the crystallizer is clarified and returned to the absorber as scrubbing liquor. The gypsum product is dewatered by rotary drum filter and conveyed to a storage area. The process has been developed by Chiyoda Chemical Engineering and Construction Company, Ltd., Yokohama, Japan.

4. Dowa process. Following an ESP for particulate removal, stack gas is contacted in a mobile-bed absorber with an aluminum sulfate solution to remove SO_2. A bleedstream from the absorber is contacted with air in an oxidizer to convert aluminum sulfite to aluminum sulfate. The aluminum sulfate is reacted with limestone in neutralizing tanks to form the gypsum product and regenerate scrubbing liquor which is recycled to the absorber. Limestone feed is wet ground prior to addition to the neutralizing tanks. The gypsum product is dewatered by thickener and drum filter and conveyed to a storage area. The process has been developed by the Dowa Mining Company, Ltd., Tokyo, Japan.

Design and economic factors chosen to provide a consistent base for comparison of the processes are defined below.

1. Project schedule and location. Project assumed to start in mid-1975 with a 3-year construction period ending mid-1978. Average cost basis for scaling, mid-1977; startup mid-1978. A midwestern plant location is assumed.

2. Power unit size and status. Costs are projected for a 500-MW new power unit. Heat rate is 9 kBtu/kWh. New units are designed for a 30-year life, 127,500 hours of operation.

3. Fuel type. Coal assumed for this study is bituminous--12 kBtu/lb, 12% ash, 3.5% sulfur (dry basis).

4. Particulate removal and disposal. A 99.5% efficient ESP has been assumed. Cost of particulate removal and disposal is not included in the economic evaluation.

5. SO_2 removal. Removal of 90% is specified as the base value.

6. Sludge disposal. Pond for the disposal of sludge from the limestone slurry process is located 1 mile from power plant. Water balance is based on closed-loop operation.

7. Capital charges. Regulated (profit and taxes included) economic basis is used. Revenue requirement estimates utilize a base value of 14.9% of fixed investment (10% cost of money).

8. System design. Design is assumed to be developed (not "first of a kind"), no redundancy is included, only pumps are spared, and an experienced design and construction team is assumed to be utilized.

A summary of the revenue requirements for 7000 hours of operation is presented in Table S-1.

TABLE S-1. SUMMARY OF TOTAL ANNUAL REVENUE REQUIREMENTS

(Excluding credit for sale of abatement gypsum)

FGD system	Total annual revenue requirements, $	Mills/kWh	¢/MBtu heat input	$/ton coal burned	$/ton sulfur removed	$/ton gypsum produced	Gypsum produced, tons/yr
Limestone slurry	10,105,300	2.89	32.08	7.70	281.64	-	-
Limestone-gypsum	12,098,100	3.46	38.41	9.22	337.18	50.21	240,960
Chiyoda	15,483,400	4.42	49.15	11.80	431.17	77.88	198,800
Dowa	10,472,200	2.99	33.25	7.98	291.62	52.53	199,360

a. Basis
500-MW new coal-fired power unit.
3.5% sulfur in coal.
90% SO_2 removal.
7,000-hour/year operation.
Mid-1978 cost basis.
Onsite disposal of limestone sludge.

The Dowa process has the lowest cost of the gypsum processes estimated. However, the technology has not been fully developed for use on coal-fired boilers. Therefore, limestone-gypsum process costs are used as a basis for estimating production costs in the following sections. Lower cost limestone-gypsum processes are currently being developed (1).

Potential Supply of Abatement Gypsum

Cost factors and premises developed in the base-case estimates were applied to operating characteristics of each steam plant in the industry. Operating characteristics were taken from Federal Power Commission (FPC) data that had been supplied by the utilities. There were 187 plants calculated to be out of compliance. FGD costs were calculated for both the limestone scrubbing and the limestone-gypsum processes for each plant. Based on the cost calculations, 116 plants are candidates to install an FGD system. The remaining 71 plants are assumed to purchase low-sulfur fuel to meet compliance. Three plants were located in the West and are assumed to install the limestone slurry throwaway system. The remaining 113 plants are subjects of the market analysis.

Each of these plants was assumed to install the limestone slurry process unless revenue from gypsum sales could be predicted to offset or exceed added costs of the gypsum process. Total first-year cost to operate the limestone throwaway process was calculated at about $2G (G = 1 billion) which includes depreciation and ponding costs. Over 25 Mtons of calcium solids would have to be discarded.

Differential costs between the limestone and limestone-gypsum processes ranged from negative $13 to positive $20/ton of gypsum. Potential gypsum production is 27 Mtons, almost twice the projected 1978 consumption in the Eastern States. Fifteen power plants could control SO_2 emissions by the gypsum process at a lower absolute cost than by the throwaway process. These plants could produce a total of 863 ktons in the first year. An additional 25 plants could meet compliance by producing gypsum at incremental cost of up to $3/ton (the estimated cost of mining crude gypsum). These 25 plants could produce 3.6 Mtons.

Negative or low incremental costs of the gypsum process were shown to occur at new, small, power plants where annual gypsum production volume is low. All negative costs were associated with relatively new plants that would produce less than 100 ktons of gypsum annually.

Results of Market Model

A modified linear programing model was used to calculate revenue from abatement gypsum sales to each steam plant. The model was based on the premise that FGD systems are mutually exclusive and that both limestone and limestone-gypsum systems will not be installed at the same plant. Gypsum production will be either zero tons or the maximum to be produced at compliance. Gypsum will only be produced and supplied when revenue can be predicted to offset added production cost.

The market analysis was conducted and presented in a series of scenarios with progressively more stringent marketing restrictions to predict the number of plants that would choose the gypsum alternative. Each scenario was developed in the same manner that a specific steam plant might employ to determine the market potential for the individual plant. Restrictions were developed to predict the steam plants which could lower cost of compliance by producing and marketing abatement gypsum if all plants were to enter the industry in 1978.

The analysis was conducted in such a manner that savings to the gypsum users could be calculated along with lowered cost of compliance to the utility industry. The final market solution predicted that 30 steam plants could lower cost of compliance by producing and marketing gypsum; the locations are shown in Figure S-1. These 30 plants would serve a total of 93 demand points. The location of demand points is shown in Figure S-2. Only one wallboard plant would purchase abatement gypsum (partly because cement plants offer a higher price outlet). Compliance cost would be reduced in the first year by \$11M to the 30 power plants compared with use of limestone scrubbing. This amounts to an average savings of over \$350k/plant. In terms of total industry cost of compliance, the savings by gypsum production would amount to less than 1%. Savings to the gypsum industry are calculated to equal \$1M. Total gypsum production is 2.4 Mtons with an average production of 80 ktons/plant. The total is approximately 53% of the amount that could be produced and sold (at \$3/ton) with costs lower than limestone scrubbing.

Abatement gypsum would be purchased by 92 cement plants. Abatement gypsum would replace 67% of the projected use of crude gypsum by cement plants. Cement plants were projected to import 1.1 Mtons. Production from the 30 steam plants would replace 74% of the imported material used in cement plants.

Use of gypsum-producing technology at the 30 power plants would solve only 8.7% of the electric utility sulfur oxides compliance problem and reduce the required ponding of calcium solids by 8.0%. Construction of "across-the-fence" wallboard plants at new power plants might improve the market potential.

The market model was also used to assess the feasibility of gypsum production and marketing assuming that wallboard plants were the only effective market outlets for abatement gypsum. Under this condition, only nine utilities could reduce compliance costs by producing and marketing abatement gypsum to the wallboard industry. These 9 plants could produce and market a total of 608,000 tons of abatement gypsum on an average of 67,500 tons/plant. Total reduction in compliance cost for the 9 plants in comparison to the limestone throwaway system would amount to \$1.6M or an average of \$184k/plant.

The reason that the wallboard market is so limited is that existing plants are built at the same location as the gypsum mine or at the point of minimum water transportation costs. Cement plants, on the other

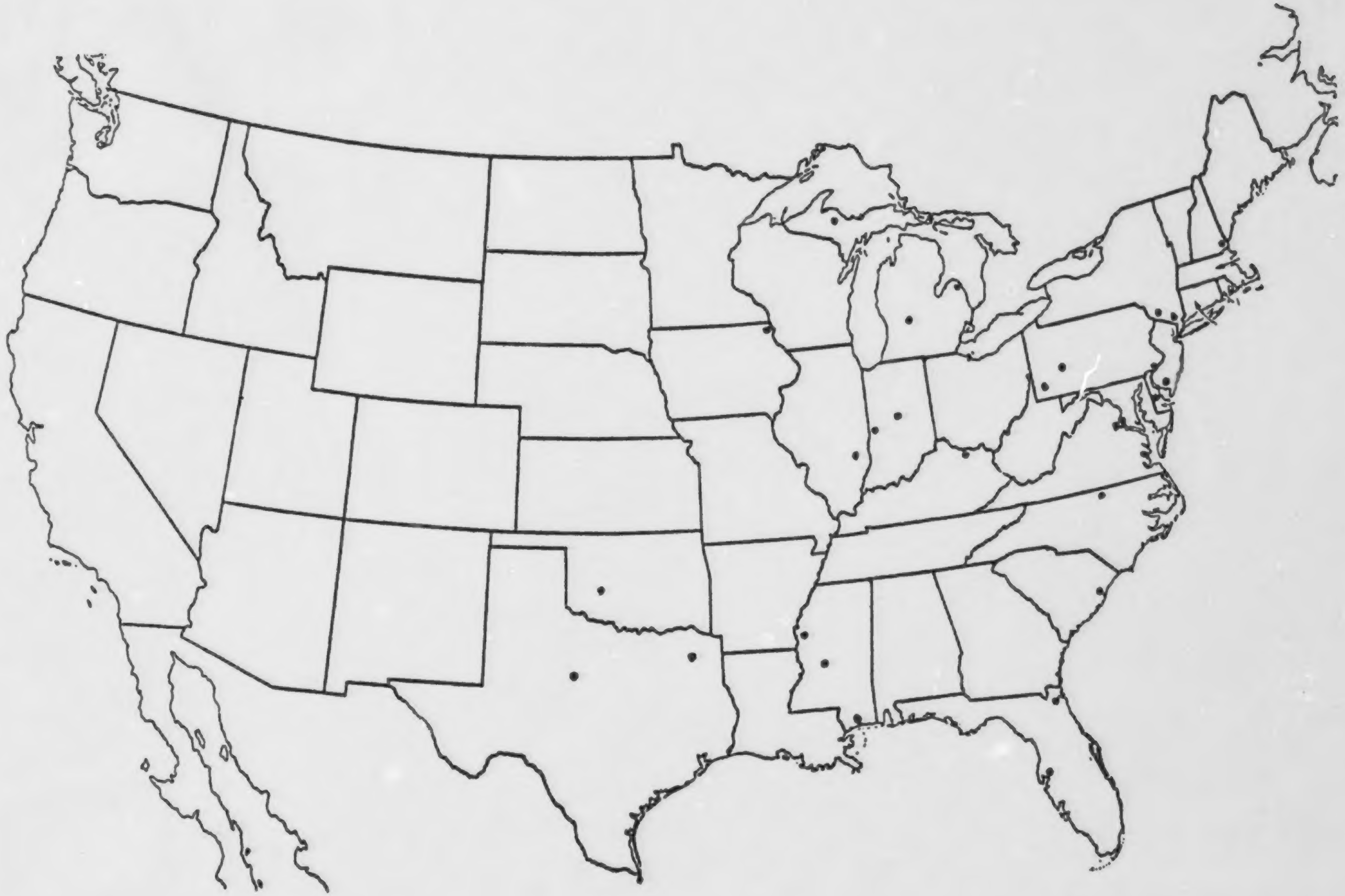

Figure S-1. The locations of steam plants that could lower cost of compliance by producing and marketing gypsum.

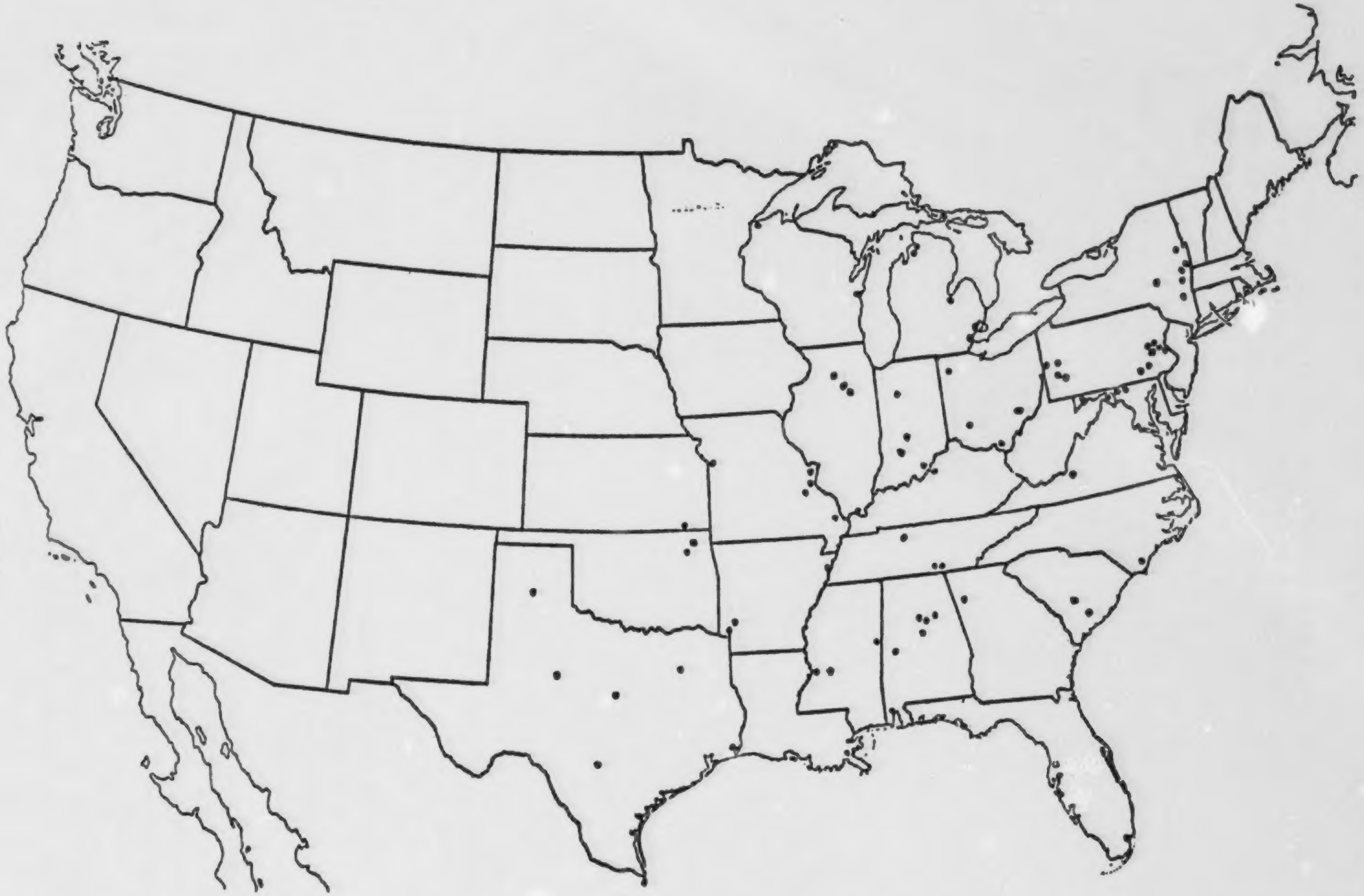

Figure S-2. Location of demand points for byproduct gypsum produced by steam plants.

hand, are not located at gypsum mines and a high percentage of the cost of crude gypsum is transportation cost rather than product cost.

An analysis was conducted based on a $3/ton price reduction to cement plants. Under this lower price assumption, 27 utilities would still reduce compliance costs by producing and marketing abatement gypsum. This compares with 30 utilities found under conditions projected for 1978. The reduction in abatement gypsum sold would amount to 365 ktons. Under the reduced price assumption, the major difference in outcome of the analysis was that savings in compliance cost for power companies was reduced from $11M to $6.2M.

CONCLUSIONS

1. Because of huge reserves, no major national interest would be served by subsidizing abatement production to serve as a stockpile for later use.

2. Gypsum production and marketing offers a limited potential to the utility industry to lower cost of compliance; only about 8% of the electric utility compliance problem would be solved by this method. Production cost relative to throwaway use of limestone scrubbing is too great for large plants which contribute the major share of SO_2 emissions. Incremental cost of producing gypsum is greater than the estimated mining costs for natural gypsum on approximately 85% of total possible abatement production. Only about half of the gypsum that could be produced and sold (at a price of $3) with costs lower than limestone scrubbing was marketed.

3. Gypsum production and marketing appear to be a viable alternative for relatively new, small plants (generally less than 200 MW) where required SO_2 removal amounts to 20-30 ktons of sulfur annually. These producers could more easily find a nearby market (cement plant) where they could compete with gypsum shipped from the mine or port of entry.

4. When viewed in a total program of byproduct production and marketing, gypsum takes on added significance in that it is particularly well suited to the segment of the industry with a small annual volume of required sulfur removal.

5. Cement plants offer the greatest potential market outlet for abatement gypsum; the wallboard industry would provide an extremely limited market. The demand at cement plants averages 25 ktons/plant and offers the possibility for about 30 steam plants to locate a few local market outlets for abatement gypsum.

6. Abatement gypsum appears to offer fewer problems in the manufacture of cement than in wallboard because impurities are not as critical.

7. Price reaction by gypsum producers cannot be predicted, but 27 steam plants would be predicted to continue to produce and market abatement gypsum to the cement industry in the face of a $3/ton price reduction.

8. Stability of the solution may be further ensured since such a high proportion of abatement market is gained by replacing imported gypsum.

9. Because of the low value of natural gypsum, production of abatement gypsum has limited potential. Special marketing opportunities may develop where across-the-fence delivery is feasible or where costs for sludge disposal from limestone scrubbing are extreme.

10. Agricultural use of gypsum represents a minor part of the total market. If forecasts of increasing soil sulfur deficiencies are correct, agricultural use will be a potential growth market for sulfur products, including gypsum.

In addition to the findings generated by this study and a companion study (2), other specific accomplishments may be cited.

1. Specific supply and demand data bases for crude gypsum were established and may be maintained or improved.

2. A computerized system for approximating rail rates was developed in conjunction with the study series and is being maintained.

3. Operating characteristics at the boiler level were projected for each fossil-fired power plant in the United States and placed in a data base for future use.

4. A computer model was developed to test for compliance and to calculate FGD costs for a number of alternative systems.

5. Procedures and models were established to calculate net revenue from sales of byproducts from steam plants.

6. Support is being generated to maintain and improve on the work developed to use the models to assist individual utilities in their efforts to develop appropriate plans for compliance.

LIMITATIONS

The analysis was conducted under the assumption that abatement gypsum is interchangeable with crude gypsum for use in wallboard and cement. Both advantages and disadvantages are likely. Tests under plant conditions, particularly in cement manufacture, need to be conducted to quantify cost associated with the use of abatement gypsum.

Further work to quantify the supply price of crude gypsum of producing areas is needed. The use of estimated average costs for all regions detracts from the accuracy of results but probably does not affect the conclusions. In that regard, gypsum industry cost information is not generally available; it is difficult for a researcher outside the industry to develop the intimate knowledge of the industry required for in-depth analysis. This study should serve to establish potential, but specific studies need to be conducted for each potential producer to more accurately determine actual cost and revenue opportunities.

RECOMMENDATIONS

For planning future growth in both the utility and gypsum industries, the special situations where production of abatement gypsum has good economic potential should be identified. This will require a cooperative effort between specific companies.

The study suggests that production of abatement gypsum as a waste product may be a viable option to disposal of sulfite sludge. Economic and environmental considerations should be evaluated.

Cost models developed can be used to evaluate compliance alternatives. This should be particularly helpful in planning for new power plants and in evaluating the effect of changing regulations.

The results of this study and any refinements should be used by the cement industry to evaluate potential supply of lower cost raw materials.

FEASIBILITY OF PRODUCING AND MARKETING BYPRODUCT GYPSUM FROM SO_2 EMISSION CONTROL AT FOSSIL-FUEL-FIRED POWER PLANTS

INTRODUCTION

The electrical utility industry in the United States faces many difficult problems and decisions in implementing the Clean Air Act of 1967 as amended in 1970 with respect to SO_2 emissions. Control strategies, such as dispersion by the use of tall stacks and reduced production during periods of weather stagnation, have been eliminated by recent court decisions. Even so, pressure continues for electric utilities to expand production. The U.S. Department of Interior has projected that net electrical generation by fossil-fired power plants will increase from 1310 GkWh (G = 1 billion) in 1971 to 1950 GkWh in 1980 (3). Utilities are expected to meet these increased power demands and to assure that emissions of sulfur oxides comply with existing air quality laws and regulations.

Current and long-term natural gas and crude oil shortages limit their use. Also low-sulfur coal is not available in adequate supplies near the point of use to meet existing needs. The remaining currently viable option, if fossil fuels are to be used, is directed to some form of emission control by desulfurization (scrubbing) of flue gases.

In recognition of the complex problems faced by utilities, the U.S. Environmental Protection Agency (EPA) has begun a broad-scale research effort with the Tennessee Valley Authority (TVA) to evaluate alternative flue gas desulfurization (FGD) systems.

Much of the early research work on FGD systems centered around the lime and limestone slurry processes. These systems are the most fully developed and in general are the lowest cost processes for coal-fired units; most installed FGD systems are lime or limestone systems. The end product is a thixotropic sludge that presents disposal problems. In 1975, EPA projected that FGD control systems could be installed on 90 kMW (k = 1 thousand) or about 35% of the total estimated coal-fired utility generating capacity by 1980. The installations would result in an annual production of 131 Mtons (M = 1 million) of throwaway sludge if the limestone slurry process were used (3). A more recent estimate (4) indicates that 109 FGD systems with an equivalent rating to over 55 kMW are either operational, under construction, or planned. Application of stack gas scrubbing by U.S. utilities now totals about 10 kMW of capacity. Lime-limestone throwaway systems are used on over 90% of this capacity.

The limestone slurry process is wasteful of large quantities of sulfur, a valuable economic resource. To the extent that SO_2 emissions can be economically recovered and used, society would be the net beneficiary. A TVA study (5) indicates total SO_2 emissions equivalent to 24 Mtons of sulfur are amenable to recovery. This is about twice the current annual use of sulfur in the United States. These factors are particularly important when it is recognized that reserves of natural sulfur in the United States are limited. Pearse (6) projects depletion of U.S. reserves by the year 2000 if mining continues at current rates. Other studies, while tending to confirm the long-run outlook for sulfur, point to possible or even probable oversupplies of sulfur in the near future. Farmer (7), for example, reports "world oversupply of sulfur is a virtual certainty for at least another decade . . . introduction of abatement sulfur (from refineries, smelters, and utilities) into domestic markets will be difficult to accomplish without causing chaos in the market." However, he suggests that by 1990 abatement sulfur will need to be captured in usable form.

The current sludge disposal procedure generally is to provide sludge-holding ponds. Disposal, depending on the unique circumstances of a particular utility, can be quite expensive. Disposal sites may have to be located some distance from scrubbing facilities. Also, it may be necessary to line disposal ponds with an impermeable material to prevent leakage. In some cases sludge has been chemically treated to produce a solid material with greater strength and lower permeability. Because sludge disposal poses potential problems of aesthetics, land use, and pollution of ground water, research is needed on long-range solutions to these potential problems including the associated costs.

Alternatives to the throwaway FGD systems are being developed that can be used to comply with regulations, but feasible application of these systems is complex, involving both technology and markets. Production and sale of abatement products marketing is a possible solution, but questions arise concerning status of technology, cost of processes, available markets, and the price effect of introducing abatement products into existing markets. Solutions to minimizing cost of compliance will be found at individual plant levels. Action taken by the utility has a major influence on options remaining for other utilities. As spatial market considerations come into play, the production and sale of an abatement product by one utility may effectively eliminate market opportunities for other potential abatement producers of the same product.

One alternative to the throwaway FGD systems is one which produces abatement gypsum. In Japan several such processes have been developed and are in use in oil-fired plants. The gypsum produced is currently being used in the wallboard and cement industries in Japan.

It is important to evaluate abatement gypsum FGD systems under existing conditions in the United States. The product has immediate uses that may contribute toward providing alternatives to throwaway systems and also has a long-run potential as a way to stockpile sulfur for future needs. In the United States, a demonstration gypsum-producing FGD system on a coal-fired facility is being operated by the Gulf Power Company of Pensacola, Florida, in cooperation with EPA; the product has been used successfully in tests at a commercial wallboard plant.

Today's market for gypsum totals nearly 20 Mtons annually, of which about one-third is imported. Gypsum markets represent a potential to use large quantities of abatement product rather than resorting to conventional throwaway systems. Gypsum may be stockpiled easily with minimal environmental problems and may be utilized later as a source of sulfur if needed. One commercial venture to produce elemental sulfur from gypsum was carried to production stage in 1968. The plant was based on a process requiring 6 tons of gypsum to produce 1 ton of elemental sulfur. At gypsum prices of $0.50/ton, the production cost of sulfur was reported between $27.00 and $40.00/long ton of elemental sulfur (8).

OBJECTIVES OF THE STUDY

The purpose of this study is to determine and evaluate the economic potential of production and marketing of abatement gypsum by fossil-fired utilities as a method to meet air quality regulations. To accomplish this evaluation it is necessary to provide a comprehensive assessment of costs of abatement systems as well as markets in which the product might be used. The study is limited to an evaluation of potential use in existing markets. The wallboard products manufacturing industry is the dominant user of crude gypsum. This market potential is given major attention, but consideration is also given to potential uses in other markets.

The major objectives are:

1. To identify basic conditions of supply and demand for the gypsum industry.
    a. Determine supply locations of crude gypsum.
    b. Estimate supply prices of crude gypsum.
    c. Estimate demand for gypsum by specific location, quantity, and price.
2. To characterize demand and projected growth in demand by major markets.
3. To identify potential problems in market entry and suggest market strategies.

4. To evaluate costs for several different gypsum-producing FGD systems and to develop cost estimates for representative systems.

5. To further develop and improve an analytical model for conducting abatement product marketing investigations.

6. To apply the model to determine optimum strategies for the industry on a plant-by-plant basis and in total.

7. To suggest further research needs.

BACKGROUND OF STUDY

TVA has been involved in research concerning SO_2 and other emissions from fossil-fired utilities for many years. Since the late 1960's, TVA has conducted research of a broad scope in cooperation with EPA; results of a number of studies have been published in the past few years. In 1975 TVA published results of a detailed cost study (9) in cooperation with EPA. This effort was a major achievement; it was the first detailed comparative evaluation and cost estimation of currently available approaches to FGD. Engineering cost estimates were developed for both new and existing facilities for 200-, 500-, and 1000-MW-capacity plants using both oil and coal at varying levels of sulfur content. At the same time methods for scaling costs for other size operations were developed. The processes evaluated were (1) lime-limestone with pond disposal of solids, (2) magnesia slurry scrubbing with regeneration to produce sulfuric acid, (3) sodium sulfite/bisulfite scrubbing with SO_2 reduction to sulfur, and (4) catalytic oxidation to produce 80% sulfuric acid.

The next logical step was to develop procedures to evaluate market potentials and market impacts for products that might be produced by the utility industry on a broad basis as well as an individual plant basis.

TVA undertook the task of developing computer procedures from which costs at each plant could be calculated and markets evaluated. The objective was the development of models and procedures for continuing use. The first effort in this direction was an economic evaluation of the potential for TVA to produce and market sulfuric acid at each of its fossil-fired plants (10). A later report evaluated the impact on the sulfuric acid market if all utilities east of the Mississippi River were to attempt to produce and market abatement acid. This study showed the equilibrium market solution when both the sulfuric acid and utility industry operated to minimize the cost of sulfuric acid to the industry (11). The study is being updated to project 1978 operating conditions of the utility industry and is being expanded to include the continental United States.

The success experienced in Japan in producing and marketing abatement gypsum for use in wallboard manufacture caused an interest in evaluating gypsum-producing systems for possible use in the United States. In 1974 a preliminary feasibility report of abatement gypsum production in the United States was completed. The findings indicated that "production of wallboard-quality byproduct gypsum from SO_2 removal systems may be an economically attractive route to waste solids disposal." A more detailed study was recommended (12). The current study results from this earlier interest and the preliminary findings.

METHODS AND PROCEDURES

The essential data management system contains four elements (1) the ability to calculate abatement gypsum production costs at individual plants, (2) gypsum market information, specifically supply locations, supply prices, demand points, and estimates of quantity demand at each point, (3) the ability to generate rail transportation cost, and (4) a linear programing model to determine least-cost distribution of crude and abatement gypsum to demand points.

The study is based on projected 1978 conditions. Abatement gypsum production cost estimates and scale factors are developed following procedures and assumptions made in the previous TVA cost study (9).

It is assumed that compliance at each plant will be achieved by 1978 with the following alternative strategies (1) using high-sulfur fuels and building limestone-scrubbing facilities including sludge disposal ponds, (2) using high-sulfur fuels and building scrubbing facilities to manufacture byproduct gypsum of wallboard quality, (3) making necessary plant modifications and changing to low-sulfur (clean) fuel, and/or (4) following a mixed strategy where clean fuel is utilized in some boilers and an FGD system is installed on other boilers at the same plant. The clean fuel alternative provides a cost screen and is held constant.

Selection of the gypsum-producing alternative depends on the cost difference between the limestone-gypsum and the limestone-scrubbing methods. If net revenue from sale of abatement gypsum equals or exceeds the cost difference, then gypsum production presents an economic alternative. Potential markets are determined by comparing the delivered prices of crude gypsum and abatement gypsum at specific demand points by linear programing procedures.

For purposes of this study, it is assumed that the gypsum-scrubbing process used in the study will effectively remove SO_2 emissions from coal-fired power plants without technological problems. It is further assumed that the resulting abatement gypsum will substitute for crude gypsum in each of its major uses. The basis for these assumptions is covered in a later section of the report.

In the short run, markets for gypsum will be dependent upon the demand for products at existing wallboard fabrication and cement plants. In the long run, optimum plant locations may change as a result of changes in demand for gypsum products and available supplies of abatement gypsum.

It is assumed throughout the study that utilities will only act as suppliers of abatement gypsum to the existing gypsum products industry. No attempt is made to evaluate the economic feasibility of the production and sale of prefabricated gypsum products by the utility industry or of relocation of wallboard or cement industries near power plants.

ORGANIZATION OF THE STUDY

The study is being conducted under contractual arrangements between TVA and EPA, is based on data projected to 1978, and covers the continental United States. The electric utility industry is the primary audience to which this study is directed, with the potential of the utility industry to economically produce abatement gypsum and replace crude gypsum being the focal point of the analysis.

The analysis is developed in four steps. The first deals with the nature of supply and demand for crude gypsum. Gypsum reserves, mine locations, mining cost, industry structure, entry conditions, and other general information relating to the overall gypsum industry are presented. Characteristics of major markets are defined, estimates of growth in markets are made, and specific demand and supply points are determined. The second step compares gypsum production costs at each utility with the limestone slurry throwaway system based on data from the Federal Power Commission (FPC) (Form 67)--cost differences between the processes are used to determine the supply quantity of abatement gypsum and price at each steam plant. The third step evaluates the market for abatement gypsum in competition with crude gypsum. A linear programing transportation model is the basic tool of analysis to determine the potential net revenue from abatement gypsum production and sale at each steam plant. In the fourth step conclusions and recommendations for further research were developed.

THE GYPSUM INDUSTRY

An overview of the gypsum industry is provided with emphasis on crude gypsum supply with which abatement gypsum supply must compete. Gypsum is defined and major uses are identified. The history of the industry is traced to the present. Supply is addressed from the point of view of existing reserves, mine locations, mining costs, and domestic and foreign production for markets in the United States. In addition, industry characteristics, structure, integration, concentration, entry conditions, and prices are discussed.

THE MINERAL GYPSUM

Gypsum is a naturally occurring nonmetallic mineral found in huge deposits in many parts of the world. Deposits are usually associated with large salt deposits and are formed by evaporation processes in orderly stratigraphic beds with limestone and salt. Gypsum is the dihydrate form of calcium sulfate ($CaSO_4 \cdot 2H_2O$) and anhydrite is the anhydrous form ($CaSO_4$). Usually gypsum and anhydrite are found in close association, but anhydrite is of limited economic importance.

Gypsum deposits contain impurities usually in the form of anhydrite, limestone, dolomite, or shale and clay. Minimum purity of 70% $CaSO_4 \cdot 2H_2O$ is required for classification as gypsum. Gypsum produced for calcining is normally 85% or greater. For agricultural purposes purity may be in the range of 50-70% $CaSO_4 \cdot 2H_2O$. In this percentage range the product is known as gypsite. Much of the gypsum used for agriculture in western states is of the gypsite quality.

The major economic importance of gypsum is derived from its unique property of readily giving up water of crystallization with application of only moderate amounts of heat. The process, known as calcining, involves heating crude gypsum at about $350^{\circ}F$ for over an hour (13). The calcined product is called "plaster of Paris" ($CaSO_4 \cdot 1/2H_2O$) which when mixed with water returns to the dihydrate form that is then manufactured into plasters for construction and industrial use and into wallboard and other prefabricated gypsum products for use in construction. Today, about 70% of the gypsum used in the United States is calcined. The remaining 30% is used in its natural state (uncalcined), primarily in the cement industry as a set retarder but also in a variety of agricultural uses (14).

HISTORY

Gypsum has been in use since the earliest recorded history. It was first used in artistic work by the Chinese, Assyrians, and Greeks. In the 18th century, gypsum was used as a soil conditioner in Western Europe. Gypsum was first discovered in the United States in New York State in 1792. By 1875 it had been discovered in six additional states and was used for agricultural purposes.

In 1885 a commercial method of retarding the setting of gypsum plaster was developed. This method permitted the use of plaster in construction (13). Then in the early 1900's the "sackett" and "folded edge" patents were announced. These patents made possible the industry's first attempts at prefabrication and have been the basis on which much of the industry has developed (14).

Gypsum production first reached a million tons in the United States in 1903. By the mid-1920's production reached 5.6 Mtons, of which 4 Mtons was calcined mostly for use in building plasters. Production declined sharply during the depression, and it was 1946 before production again climbed to 5 Mtons. This increased production was primarily to meet wartime needs for prefabricated products for temporary military buildings.

The industry entered a period of rapid growth shortly after World War II to meet the demand for new housing. In 1947 total value of gypsum products sold was $127.5M; by 1967 the total value of sales had increased to $387.7M; and the value of sales in 1974 exceeded $630M. During the same period the gypsum industry also went through a major change in terms of composition of sales. Immediately prior to World War II the value of shipments of gypsum products was about evenly divided between building lath and plaster, each with about 33% of the market; sales of prefabricated wallboard products amounted to 23% of value of sales. During the war the dry-wall product was used extensively and became the major user of gypsum. That trend continued after the war, and the use of wallboard products has continued to expand. By 1974 sales of prefabricated dry-wall products were 86% of the value of sales while lath and plaster declined to 2 and 4% respectively. Uncalcined products made up 6% of the total value of gypsum sales.

GYPSUM RESERVES

In the preprint from Bulletin 667 (13), the U.S. Bureau of Mines provides the following information concerning reserves of gypsum.

> Domestic and foreign resources and reserves of gypsum are adequate for any foreseeable period of time. World reserves are conservatively estimated at 2 billion tons, of which the United States has 350 million tons. Canada has tremendous gypsum resources in Nova Scotia, New Brunswick, Ontario,

Manitoba, British Columbia, and Newfoundland. Reserves are estimated at 410 million tons, but Nova Scotia alone has 600 square miles of gypsiferous rocks.

The reserves of gypsum in the Paris Basin in France are considered to be almost unlimited. The gypsum beds extend over 8,000 square kilometers with thicknesses up to 55 meters.

Most of the countries bordering the Mediterranean have large to very large gypsum deposits.

In the United States, gypsum resources are centered near three main areas, the Great Lakes area, California, and the Texas-Oklahoma area. In Michigan, a continuous belt of gypsum-bearing rocks underlies parts of Kent, Iosco, Mackinac, Ionia, Saginaw, and Eaton Counties. These resources of gypsum are practically inexhaustible.

Texas has very extensive gypsum resources. The largest area of gypsum deposits extends for 200 miles from Sweetwater on into Oklahoma, 20 to 50 miles wide and up to 20 feet thick. In Culberson County, gypsum outcrops over 600 square miles, 50 miles long, 15 miles wide, and up to 60 feet thick.

The Texas deposits continue into Oklahoma, where enormous gypsum resources occur. The gypsum deposits underlie most of Beckham, Greer, Jackson, and Harmon Counties. Other large deposits occur along the Cimarron River and in the west-central part of the state.

In Webster County, Iowa, an area of 70 square miles is underlain by gypsum beds up to 30 feet thick. The area is 13 miles long and 5 miles wide.

Many deposits of gypsum and gypsite occur in California. The total resources are very large.

Other states have large gypsum resources. In southeastern Arizona, there are two gypsum beds, each 50 feet thick. In Colorado, there are several gypsum beds up to 30 feet thick. There are large deposits in Indiana. Gypsum

> beds in Kansas are said to be inexhaustible. Montana has several gypsum beds up to 30 feet thick. In Nevada, gypsum beds range up to 130 feet thick. In New Mexico, there are gypsum beds up to 100 feet thick, and white sand dunes of gypsum cover an area of 270 square miles. Enormous beds of gypsum up to 200 feet thick are found in Utah.

Gypsum reserves are extensive both in the world and the United States; however, with the exception of one gypsum-producing area in southwest Virginia no economic reserves are located in the southeastern portions of the United States.

Data are not available concerning ownership of reserves by companies, but distinct differences in composition of the industry in western reserves compared to reserves in the East lead to the assumption that economic reserves in the East are under the control of integrated companies. This may partially be explained by limited noncalcined markets for gypsum in the East. The nonintegrated mine operator would be dependent upon the cement industry for his market outlet; the cement industry would offer limited local demand.

Transportation costs are critical to the industry. Both crude gypsum and manufactured gypsum products are bulky and have relatively low values. Freight costs to move gypsum product to distant markets soon become greater than product value. Consequently, mine and plant locations must be established in close proximity to markets served. Maps showing gypsum-producing regions, mines, and plant locations are shown in Figures 1-3. Calcining plants serving interior markets are located in close proximity to mines--many times on the same property. Coastal markets where gypsum is not available are served by calcining plants located at seaport locations that use crude gypsum imported primarily from Canada and Mexico.

GYPSUM MINING

Gypsum is mined from both open-pit and underground mining operations. Open-pit mining is done by use of conventional methods and highly mechanized equipment. Overburden is removed and shovels are used to load the rock. Production is usually in the range of 500 to 1500 tons each day (15). Underground mining is accomplished by room and pillar methods. Mining costs are low. According to Appleyard (15), many operating deposits in 1973 mined gypsum and delivered (onsite) to mill for a cost ranging between $0.60 and $3.00/ton not including depreciation.

Mining costs are most directly influenced by the amount of overburden that must be removed, the thickness, and the consistency of the deposit. Normally, no beneficiation is performed after mining; therefore,

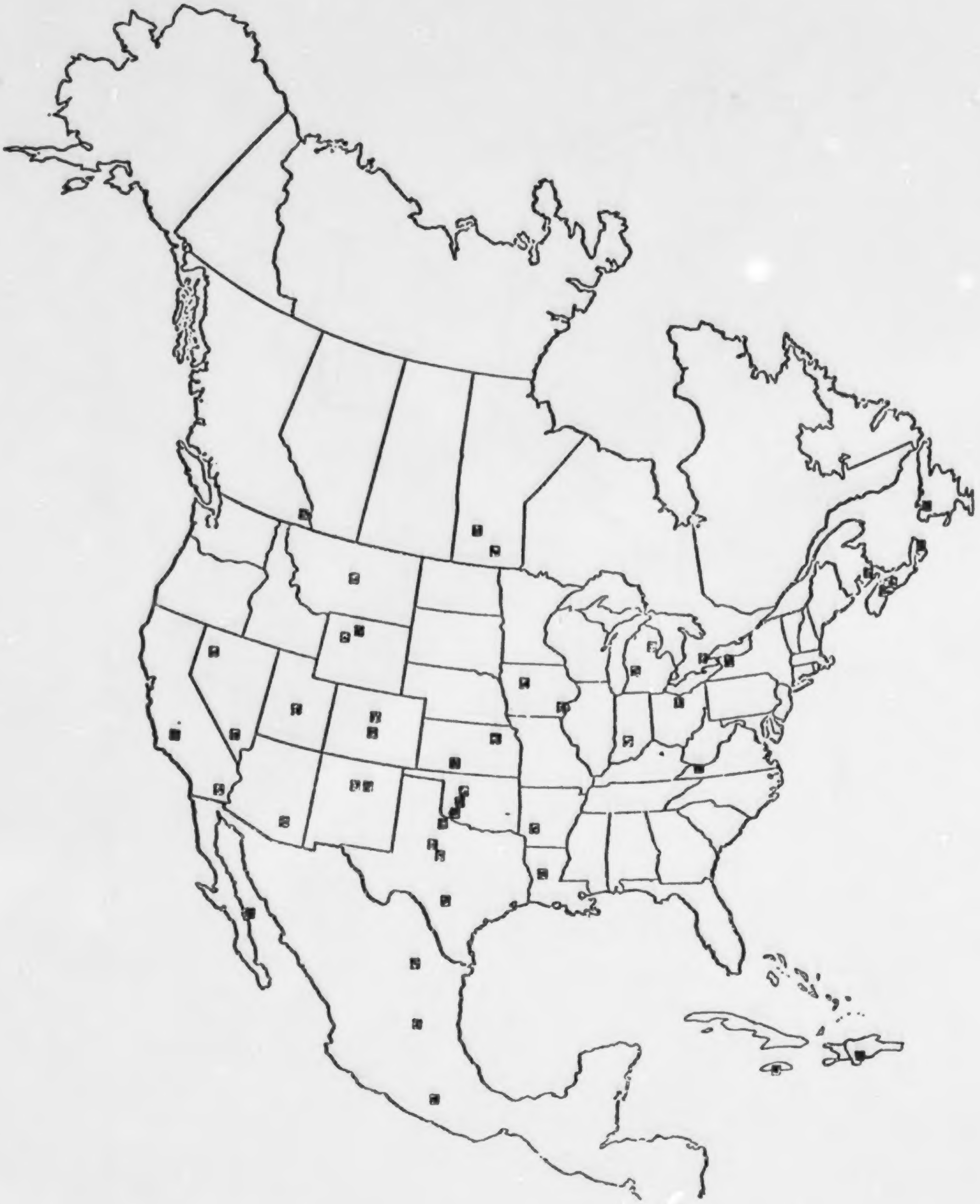

Figure 1. Location of gypsum-producing districts in North America (15).

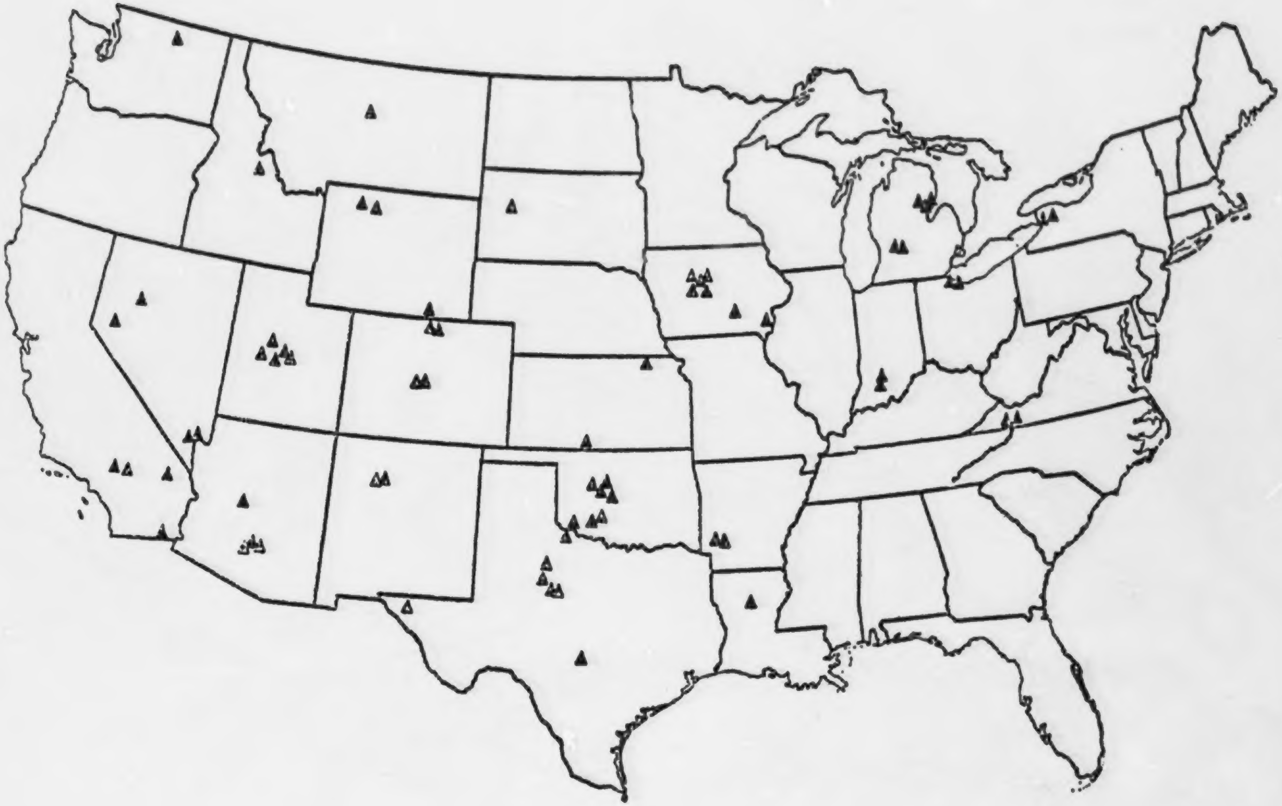

Figure 2. Location of domestic gypsum mines, 1975 *(Mineral Industry Surveys)* (16).

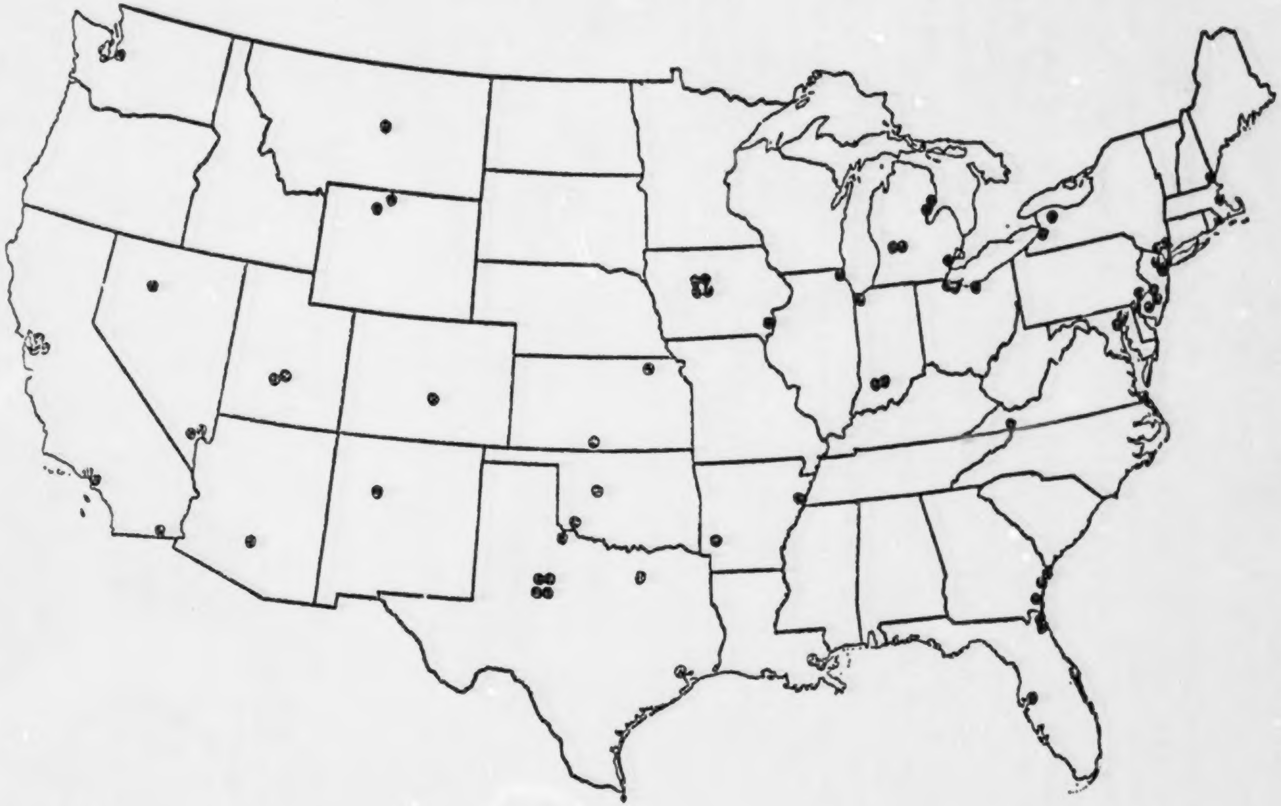

Figure 3. Location of domestic calcining plants, 1975 *(Mineral Industry Surveys)* (16).

overburden, as well as impurities within the deposit, must be carefully removed before shipping or milling to maintain the desired purity. After mining the product is milled, which for the most part consists of grinding and screening to size specifications for intended use.

Mining of gypsite in the Western States for agricultural use is the simplest operation. The deposits have very little overburden which is simply scraped away. The same scrapers are used to remove gypsite in thin layers. It is then crushed, screened, delivered, and bulk spread (17).

Domestic mining cost data are not available from published sources; however, some indicators of cost are available. Energy costs per ton in 1973 were \$0.17/ton of gypsum mined according to a survey conducted by the Bureau of Mines (18). In 1968, according to information prepared by the Bureau of Mines, the average output was 10,500 tons per employee (17). More complete information on mining costs in Canada is available from a 1974 publication of the Ministry of Industry, Trade and Commerce (19). This information is presented in Table 1 and compiled on a tonnage basis in Table 2. The Canadian information is generally comparable to that for mining costs in the United States. The summation of average wage cost, energy cost, and cost of supplies and materials should represent a good estimate of the average variable cost per ton for mining gypsum. In 1974 that figure in Canada was \$1.42/ton. This figure should provide a good estimate of the average variable cost for gypsum mined in the more economical producing areas of the United States.

Appleyard (15) discussed characteristics of the major producing areas of North America in some detail. From his discussion it is apparent that mining costs vary both within and between producing regions. Differences in cost, however, are not great enough among regions to justify cost of ground transportation. For example, crude gypsum is imported from southeastern Canada by water into lower New York State although active deposits are located in the western edge of the state.

Domestic gypsum production is centered in five states: California, Iowa, Michigan, Oklahoma, and Texas. These five states accounted for approximately 50% of total U.S. production (13). Mine production is quite variable, ranging from less than 20 ktons to 750 ktons each year. The Bureau of Mines maintains data on all mines that report an annual production in excess of 20 ktons; in 1974, 75 mines were reported. Total output was 11,999 ktons or an average of about 160 ktons each mine. Ten of the 75 produced 42% of total production in the United States or over 5 Mtons for an average of 0.5 Mtons each.

These data suggest that significant differences in minimum economic sizes of mines exist between eastern and western deposits and, of course, between underground and open-pit mines. In the Western States mines with an annual output of 20 ktons apparently compete effectively with mines many times that size. In the East this is not the case.

TABLE 1. GYPSUM MINING COSTS IN CANADA - 1970-74[a]

						Cost, k$					
			No. workers			Wages					
Year	No. firms	Gypsum sold, ktons	Production	Administration	Total	Production	Administration	Total	Energy	Supplies & materials	Value, f.o.b.
1970	13	6,319	563	108	671	3,401	881	4,282	721	2,728	14,199
1971	10	6,702	500	103	603	3,324	886	4,210	814	2,718	15,083
1972	10	8,099	567	103	670	4,280	913	5,193	874	3,521	19,336
1973	10	8,389	575	101	676	4,508	910	5,418	986	3,341	21,067
1974	10	7,967	577	94	671	4,861	992	5,853	1,101	4,258	22,437

a. Ministry of Industry, Trade, and Commerce. Gypsum Mines, 1974. In: Statistics Canada, Catalogue 26-221 Annual, Tables 1, 2, and 11.

TABLE 2. GYPSUM MINING COSTS PER TON IN CANADA - 1970-74[a]

Year	Tons/ production worker	Tons/ administration worker	Tons/ worker	Cost/ton, $			Energy	Supply & material	Value	Average variable cost, $
				Production worker	Administration worker	Worker				
1970	11,224	58,509	9,417	0.54	0.13	0.67	0.11	0.44	2.25	1.22
1971	13,404	65,068	11,114	0.50	0.13	0.63	0.12	0.41	2.25	1.16
1972	14,284	78,630	12,088	0.53	0.11	0.64	0.11	0.44	2.39	1.19
1973	14,590	83,059	12,409	0.54	0.11	0.65	0.12	0.40	2.51	1.31
1974	13,802	84,723	11,869	0.61	0.13	0.74	0.14	0.54	2.82	1.42

[a] Ministry of Industry, Trade, and Commerce. Gypsum Mines, 1974. In: Statistics Canada, Catalogue 26-221 Annual, Table 1.

INDUSTRY CHARACTERISTICS

Functions of the gypsum industry include mining and distribution of crude gypsum for direct uncalcined uses and for calcining for manufacture and distribution of gypsum products for construction and industrial uses. Total value of industry sales exceeded $630M in 1973--a record year for the industry. Calcined products made up 95% of total value of sales and prefabricated products accounted for 94% of value of sales for calcined products; value of sales includes value added in the manufacture of prefabricated products. The agriculture and the cement industries were major users of uncalcined materials accounting for 1 and 4%, respectively, of value of sales. In 1973, 20,636 ktons of crude gypsum was consumed in the United States. Production in the United States amounted to 13,558 ktons and 7,661 ktons was imported. Uses were distributed among products as follows: calcined materials, 73%; agriculture, 7%; and cement, 20% (20).

Seasonal Distribution Patterns

Since the gypsum industry is so closely dependent on the construction industry, it could be assumed the industry would be characterized by a highly seasonal distribution pattern. This is not the case based on quarterly data during 1970-74. When taken as a percentage of total annual sales of board products, distribution is almost equally divided among the four quarters. There is a slight tendency for first-quarter distribution to be slightly below 25% and the remaining three quarters to be slightly above 25%. Percentage distribution by quarters is shown in Table 3.

TABLE 3. SEASONAL DISTRIBUTION OF WALLBOARD PRODUCTS--

SALES BY QUARTERS OF THE YEARS - 1970-74[a]

	% annual total sales				
Annual quarters	1970	1971	1972	1973	1974
January-March	22	21	23	24	27
April-June	26	25	25	25	26
July-September	26	27	26	26	26
October-December	26	27	26	25	21

a. U.S. Bureau of Mines. Minerals Yearbook.

The data indicate that utilities could plan to distribute abatement gypsum on a regularly scheduled basis throughout the year. Storage facilities can be geared accordingly with flexibility to provide for outages and possible added seasonal demands if agriculture becomes a significant market.

Annual requirements are subject to wide fluctuations (see Table 4). Industry requirements, while showing an upward trend, have fluctuated by as much as 2 Mtons in a single year. From 1970 through 1973 gypsum use increased over 6 Mtons but by 1975 had decreased by 5.5 Mtons to 15,190 ktons. This was just a little more than 1 Mton above average use in the sixties. Through September 1976, use was 1 Mton greater than the same time period in 1975.

TABLE 4. GYPSUM USE, PRODUCTION, AND VALUE - 1955-75[a]

Year	Domestic use, ktons	Domestic production, ktons	Average value f.o.b., $/ton	Imports, ktons	Average value f.o.b., $/ton
1955	13,994	10,684	3.18	3,966	1.58
1956	13,676	10,316	3.31	4,336	1.80
1957	12,720	9,195	3.25	4,334	1.75
1958	13,210	9,600	3.38	4,049	1.70
1959	15,200	10,900	3.59	6,135	1.94
1960	14,008	9,825	3.63	5,301	1.70
1961	13,692	9,500	3.68	4,967	1.82
1962	14,514	9,969	3.65	5,421	1.94
1963	15,155	10,388	3.67	5,490	1.98
1964	15,879	10,684	3.64	6,258	2.13
1965	16,092	10,033	3.73	5,911	2.37
1966	14,778	9,647	3.70	5,479	2.37
1967	14,132	9,393	3.66	4,563	2.87
1968	15,625	10,018	3.67	5,474	2.08
1969	15,818	9,905	3.88	5,858	2.12
1970	14,334	9,436	3.72	6,128	2.24
1971	16,914	10,418	3.75	6,094	2.21
1972	19,412	12,328	3.93	7,718	2.38
1973	20,636	13,558	4.18	7,661	2.30
1974	18,693	11,999	4.41	7,424	2.37
1975	15,190	9,251	4.80	5,448	2.94

[a] U.S. Bureau of Mines. Minerals Yearbook.

Integration

In terms of value of product sold, the industry is highly integrated from mining through calcining and sale of manufactured products. In 1975, 13 companies operated 74 calcining plants in 29 states. Seven firms were multiplant firms operating from 2-23 plants. Six firms operated one plant each. Of the 13 firms, all but 2 operated company-owned mines that supplied gypsum to calcining plants and also sold gypsum for other uses.

In addition to being highly integrated from mining through manufacture of gypsum products, the large firms manufacture the paper stock required for prefabricated products and are also diversified to provide a variety of building and construction needs including cement and concrete products.

In general, the industry is not integrated forward. Wallboard products are sold to independent building supply dealers or building contractors. In most cases wallboard manufacturing plants have limited final product storage, but warehouses may be located in distribution areas. Also "speciality" dealers or wallboard brokers are important distributors of wallboard--especially in the California market during its period of rapid expansion in the sixties (21). Because of transportation costs, plant sizes must be geared to limited distribution areas. Plant locations shown in Figure 3 tend to demonstrate this.

When the mining sector of the industry is viewed separately, slightly different characteristics are observed. Almost all of the gypsum used in calcining operations is mined by integrated companies. These companies also supplied a large percentage of the uncalcined gypsum used in the agricultural and cement industries from both domestic and imported services. As indicated earlier, the Bureau of Mines reports annual production data from all mines with an annual production of 20 ktons or more. The number reported varies each year but ranges around 70 mines (see Table 5).

Except for one mine in Michigan, there are no nonintegrated mining operations east of the Mississippi River. Nonintegrated mining operations are in almost all cases small, one-mine operations. Output from these mines is marketed for agricultural and cement uses and geared to local demand. Since the Bureau of Mines reports data for mines with production exceeding 20 ktons annually, it is assumed that variability in number of single-mine operations actually is not as great as indicated in Table 5, but that variability in annual mine output is great. It is assumed that mine numbers are more constant than indicated but that production drops below 20 ktons frequently as local demand for cement and agricultural use varies.

TABLE 5. CRUDE GYPSUM MINE NUMBERS, CALCINING PLANT NUMBERS, AND OWNERSHIP PATTERNS - 1970-75[a]

	1970	1972	1973	1974	1975
Number of mines	69	65	69	75	71
Number of plants	76	76	77	77	74
Multiplant firms	7	8	7	8	7
Plants operated[b]	69	70	70	72	68
Mines operated[b]	34	36	36	36	36
Single-plant firms	5	5	6	5	6
Mines operated	4	3	4	3	4
Mining firms only					
Number of firms and mines	31	26	29	36	31

a. U.S. Bureau of Mines. Mineral Industry Surveys.
b. Plants operated by multiplant firms and domestic mines operated by multiplant firms.

Although a relatively large number of companies is involved in gypsum mining, the history of the industry is that almost all gypsum moving into calcining plants is from integrated operations. In 1972 Appleyard reported 11 calcining firms in operation. He further stated that the 11 firms owned and controlled their own gypsum mines.

Fertilizer manufacturing operations are also becoming important suppliers of byproduct gypsum for agricultural uses replacing crude gypsum or gypsite. In 1974 three firms in California distributed 463 ktons at a reported value of $4.3M. Although data are not available, it is known that byproduct gypsum from phosphatic fertilizer manufacturing operations in Florida and North Carolina is becoming increasingly important in supplying agricultural markets in the Southeast.

Concentration

The industry is also highly concentrated. From 1947-72 the leading four firms have accounted for about 80% of value of industry shipments in every year. (In 1954 the four-firm ratio rose to 90% but then declined to an 80% ratio where it has remained.) The leading eight firms have consistently accounted for over 90% of the market (22). Total number of firms involved in the industry has ranged from 39 to 49 since 1970. Thirteen firms have manufactured wallboard and other products.

Firm growth during the period has taken place by internal expansion, by merger, and by acquisition. A number of acquisitions in the sixties afforded entry into new market areas for the acquiring company. Almost every annual issue of the Bureau of Mines Minerals Yearbook reports plant expansions and new plant openings. In fact, plant capacity increased by 41%--from 8,388 Mft^2 of 1/2-inch wallboard in 1960 to 11,882 Mft^2 in 1968 (21). Since 1970 only one new plant has opened. Industry information indicates three plants were closed in 1975; however, that information is not reflected in currently published Bureau of Mines data.

Product Differentiation

Gypsum products are sold under brand names, but the products must be interchangeable and tailored to meet very specific construction uses. Buyers of the products are primarily building contractors who are technically well informed. Because the products are homogeneous among companies, buyers usually do not differentiate among suppliers. To increase sales and market shares, firms provide added services, technical expertise, and training. The Gypsum Association actively works to stimulate overall sales of gypsum products and to find new opportunities for use of gypsum products.

Entry Conditions

Bain (23) included gypsum products in his study "Economics of Scale, Concentration, and Condition of Entry in Twenty Manufacturing Industries." He lists three major factors affecting condition of entry to an industry, (1) economies of scale, (2) proportion of market required for minimum economic-size firm and plant, and (3) absolute cost of entry.

His findings with regard to gypsum products were that minimal efficient plant size was 2.3-3.0% of the national market. He found evidence of "small" economies of multiplant operations. Optimal firm size was found to represent 27-33% of the national industry capacity. He suggests that the optimal-size firm in the gypsum products industry would have about 10 plants. (Present distribution of the number of plants is shown in Table 5.) Regional market share of a minimal efficient-size plant must be 10% or greater. In terms of absolute costs total capital requirements for minimal efficient-size plant were $5-6M in 1951. Conversation with equipment suppliers indicates that figure has now risen to $12-15M exclusive of land costs.

Even though Bain's work was published in 1954, much of it is relevant today and should be seriously considered by potential entrants to the industry. Market share requirements for minimal plant size are probably at least as great or greater today. The percent of national market, other than a measure, is largely meaningless since prefabricated products must be sold in regional markets. The capacity of existing plants has been an elusive figure to find on a plant-by-plant basis. As indicated earlier, the industry went through a period of rapid expansion in the sixties. Available information from Minerals Yearbook indicates that several plants were built to a rated capacity of about 180-200 Mft^2 1/2-inch wallboard equivalent. These data translate into a market for about 185 ktons of gypsum per plant. Some were larger, but no evidence of smaller plants was found.

In this study an attempt has been made to differentiate industry characteristics between the mining and calcining sectors and further between eastern and western segments. Integration has apparently been a requisite for success in the gypsum products industry. Data from the Bureau of Mines indicate only two firms involved in calcining are not integrated. A knowledgeable industry participant (24) indicates that in 1972 all calcining firms controlled and operated their own gypsum mines. The two supposedly nonintegrated firms were in operation in 1972. The nature of gypsum deposits, the ability to handle impurities, and perhaps different specifications existing for different companies would all work together to make it extremely difficult to develop a viable market for crude gypsum. To the extent that integration is required to achieve minimal efficient size in the product industry, the absolute costs of entry are increased by the amount necessary to gain control of adequate reserves and open and begin operating a mine.

In western areas substantial markets exist for both cement and agricultural uses. Reserves also appear to be more widely distributed and less subject to existing industry control and mines less expensive to open. Minimum economic size of a mine appears to be perhaps as low as 20-30 ktons annually based on the number of small mines in operation. Using Bain's terminology, entry barriers into mining would be classified as relatively low. Evidence is particularly lacking to show substantial economies in multiplant firms in the western areas. Thirteen firms operated calcining plants in 1975. Six of these firms had single-plant operations and five were located in the West. Further, the most recent plant opening was accomplished by a single-plant firm expanding to operate a second plant in a new location. All single-plant firms used domestic gypsum and in all probability had a high degree of control over the supply of crude gypsum.

In the area east of the Mississippi, conditions of entry appear to be somewhat different. In the eastern and coastal areas, calcining plants are located at seaports. These plants are owned by the large integrated multiplant firms that also may own shipping lines or arrange 3-5 year contracts to transport crude gypsum from company-owned mines in Canada or other import sources. Ships have cargo capacities of up to 30 ktons. The Canadian mines, the source of over 75% of total imports in the United States, are located in Nova Scotia, New Brunswick, and Newfoundland. In addition, small amounts of gypsum are supplied to cement plants in the northwest portion of the United States from a mine near Windermere, British Columbia. Mines in the Atlantic provinces are located from 6-30 miles from seaport locations (16).

In these areas absolute costs of entering the industry would involve ownership of foreign reserves, shipping lines plus loading and unloading facilities, as well as the cost of a calcining plant. Here the economies of multiplant ownership found by Bain seem evident.

These observations indicate that abatement gypsum production by utilities would significantly lower entry costs east of the Mississippi River and slightly in other areas. If these observations are true, it would be expected that in the East and Southeast in particular, new wallboard manufacturing plants would be built "across the fence" from utilities to use the abatement product and would be located closer to interior markets. Thus, the long-run demand for abatement gypsum may be expected to change in response to new plant locations.

Prices

Largely because of the degree of vertical integration of the industry, there is no "market" for gypsum for wallboard use. Gypsum is sold by producers for use in the cement and agricultural industries. Price announcements are made to the cement industry; and as would be expected from the nature of the industry, they are changed infrequently, and the product is sold on a contract basis. In agriculture there is a degree of market and market-price establishment mechanism developing as a result of the introduction of byproduct gypsum from fertilizer manufacture.

Mining and calcining firms provide regular reports to the Bureau of Mines. These reports include the value of product at the mine. The value reported is the average net sales price received for gypsum sold during the period. Value information is reported as an average for all gypsum sales, as an average for cement sales, and as an average for sales for agricultural use. These figures are summarized on a national basis in Table 6.

Wallboard prices are on a delivered cost basis and vary widely between different sections of the country. Representative prices are published by the Engineering News Record. Prices are quoted in truckload lots delivered f.o.b. in 20 cities across the United States for 1/2-inch board. In the January 1976 publication, prices per kft^2 ranged from a low of $38.90 in Dallas to a high of $90.00 in Chicago. Review of these prices on a quarterly basis from 1972 to the present indicates the same degree of variability between cities reported, but the Dallas market is consistently the lowest and Chicago generally the highest.

TABLE 6. GYPSUM USE AND VALUE BY MAJOR CONSUMING SECTOR[a]

Year	Calcined, ktons	Average value, $/ton	Cement, ktons	Average value, $/ton	Agriculture, ktons	Average value, $/ton
1955	10,437	3.18	2,226	3.92	678	3.39
1956	9,820	3.31	2,394	4.02	830	3.37
1957	9,019	3.25	2,273	4.21	830	3.76
1958	9,227	3.38	2,416	4.23	1,021	3.30
1959	10,657	3.59	2,757	4.30	1,188	3.09
1960	9,797	3.63	2,543	4.42	1,126	3.29
1961	9,360	3.68	2,763	4.27	1,088	3.50
1962	10,035	3.65	2,765	4.47	1,241	3.40
1963	10,519	3.67	2,898	4.46	1,262	3.46
1964	10,326	3.64	2,986	4.52	1,270	3.52
1965	10,112	3.73	3,152	4.62	1,265	3.68
1966	9,826	3.70	3,372	4.62	1,276	3.96
1967	9,313	3.66	3,154	4.66	1,280	4.27
1968	10,391	3.67	3,439	4.66	1,388	4.48
1969	10,861	3.88	3,464	4.58	1,100	4.85
1970	9,953	3.12	3,358	4.74	804	5.27
1971	12,291	3.75	3,386	4.78	1,124	4.79
1972	14,217	3.93	3,924	4.94	1,146	5.21
1973	14,917	4.18	4,148	5.35	1,453	5.09
1974	12,841	4.41	4,058	5.94	1,671	7.62
1975	10,390	4.51	3,244	6.25[b]	1,482	8.00[b]

[a] U.S. Bureau of Mines, Minerals Yearbook.

[b] Estimated.

In general, prices are lower near calcining plants. Prices also tend to reflect competitive conditions in the industry although the Dallas-Chicago comparison is the most striking. Six firms produce in the Dallas area while only one is located near Chicago. The Detroit area also reports generally low prices. The January 1, 1976, price was $\$58.50/\text{kft}^2$. Four firms are located in Michigan. Sources of crude gypsum for Detroit and Chicago are both located in Michigan. Three plants in Michigan are located at mines. One is located in Detroit and crude gypsum is barged from a mine in Michigan.

The price comparisons shown tend to confirm greater difficulty of entry in the eastern market. Prices in these areas can apparently be held at somewhat higher levels without attracting potential entrants. If higher than normal profits are now being realized in this market because of effectively blocked entry, abatement production would likely reduce product prices.

Proximity to wallboard markets is a major advantage for a firm in competing for markets. If abatement production afforded an opportunity to construct new plants closer to existing markets, other producers would be placed at a cost disadvantage. Based on past history, other firms would be expected to build new plants in order to compete with the initial plant. Therefore, any new plant to be built on the basis of abatement production must be predicated on its future ability to compete with other plants using crude gypsum from conventional sources. In other words, abatement product cannot be sold for more than delivered costs of crude gypsum at the same location.

MARKETS FOR ABATEMENT GYPSUM

The previous section dealt primarily with the industry characteristics on the supply side. The potential for substitution of abatement gypsum is influenced by the factors considered in this section.

Markets for crude gypsum could be categorized by types of processes involved and by similarity of forces affecting demand for products. The Bureau of Mines (13) categorizes markets along the lines of similarity of factors affecting demand. For purposes of showing historical use patterns and for projecting future uses by markets, the Bureau of Mines has divided end uses into three major categories: (1) construction, (2) agriculture, and (3) others. Construction uses are subdivided into building uses such as plasters, prefabricated products, and a cement retarder.

TECHNICAL SUBSTITUTION

It should be clearly understood that a full technical assessment of substituting abatement gypsum for crude gypsum is outside the scope of this project. However, in the course of working on the study, some information pertinent to the technical aspects of abatement gypsum has been developed and is reported. Abatement gypsum is similar to natural gypsum and should be environmentally safe for indefinite storage as a future sulfur reserve or other purposes.

From the product specifications provided in the section on the gypsum industry, gypsum is 85% or more $CaSO_4 \cdot 2H_2O$. Impurities may be categorized into three different forms (15): (1) insoluble or related insoluble materials including clay, silica, minerals, and limestone, (2) soluble chloride minerals, such as halite or sylvite; and (3) hydrous minerals such as the sulfate salts mirabilite and epsomite and the montmorillonite group of clay.

Abatement gypsum, by comparison, is a fine crystalline material containing up to 20% free moisture. It is approximately 96% pure calcium sulfate. Impurities are 4% calcium carbonate and less than 0.05% soluble materials.

The degree and amount of impurities that can be tolerated depend on the product to be manufactured and the competitive situation of gypsum. For wallboard manufacture, to the extent that impurities replace gypsum, strength is reduced and more pounds of stucco are required to achieve a

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given strength of finished plaster or wallboard. Soluble chloride minerals affect calcining temperature, set time, and stucco slurry consistency. Soluble chlorides are limited to 0.02 to 0.03%. The hydrous sulfate salts are also limited to 0.02 to 0.03% as they affect moisture pickup and bonding characteristics of the stucco in the core of the wallboard. Hydrous clays of up to 1.0 to 2.0% may be tolerated.

Crude gypsum received at calcining plants is crushed and ranges from dust to stones of minus 8 inches. Typically, it is handled and stored outside. At the time of use the gypsum may contain up to 3% free water.

Abatement gypsum made from oil-fired power plants is being used extensively and successfully by wallboard and cement manufacturers in Japan (25). To date, there have been no commercial applications of these processes in the United States, but it is understood that at least two firms are actively studying the possibility at this time. In addition, a demonstration-scale facility using the Chiyoda process has been operated at the Scholz plant of Gulf Power Company. Samples of product made from that facility have been used to manufacture wallboard under plant conditions. Results and specific conditions of the tests are proprietary information, but, in general, the wallboard manufactured met normal quality control tests.

Gypsum is used in the cement industry as a set retarder. Cement clinkers are manufactured and stored, and as final product is needed, gypsum is added to the clinker and ground into the final product. Apparently, the SO_3 content of the gypsum is the critical factor. Anhydrite may also be used as a blend with gypsum, but most prefer straight gypsum. Approximately 5% of the reported gypsum used is anhydrite (24). There is some indication that the cement industry prefers a higher purity gypsum. A purer gypsum would permit the use of more clinker per ton thereby increasing the strength of the concrete. Abatement gypsum is approximately 96% calcium sulfate.

Abatement gypsum with a slightly different composition from that of power plants is now becoming available from the manufacture of titania pigment. Battelle of Columbus, Ohio, made laboratory studies of this product and found it acceptable for both wallboard and cement manufacturing (26). Product from at least one to four new plants is now being tested under actual wallboard manufacturing conditions.

Available evidence indicates that abatement gypsum will perform satisfactorily as a substitute for crude gypsum in its three major uses. In fact, the higher purity and greater consistency may prove to be important advantages for abatement products. Substitutability in agriculture seems assured since byproduct gypsum is already being used, and its use is increasing each year. Two disadvantages that have been found, especially regarding its use in existing cement and calcining plants, are particle size and excessive free water. Existing plants have handling equipment set up to handle rock-size (0.25-2.0 inch) gypsum.

This handling equipment cannot effectively handle the consistently small crystal size of abatement gypsum. In calcining operations the excessive free water, which is 20% as compared with 3% for crude gypsum, would have to be driven off. Because of heat in the reactions in cement manufacturing, the free moisture may not be a problem with the exception of how it affects handling qualities. New plants could be designed to handle the abatement product, or the utility could compact and dry the abatement product to overcome these problems. Also, abatement gypsum could be viewed as a source of high purity gypsum to blend with crude gypsum. The disadvantages could be minimized and the advantages fully used.

This is a very brief overview of work that has been done with abatement gypsum. This study is being conducted under the assumption of perfect substitution between abatement and crude gypsum. To determine the technical aspects of abatement gypsum and its substitutability will require more research into composition, crystal size, and structure as well as testing under operating conditions.

Phosphogypsum from fertilizer manufacture is of lower purity and its impurities preclude its use in cement or calcining operations without further processing. At existing or projected conditions, the processing costs are greater than the value of competitive crude gypsum. Phosphogypsum is not considered a factor in the study.

CHARACTERISTICS OF WALLBOARD MARKET

Gypsum products must be tailor-made to meet exacting building specifications, and purchasers are well informed. Consequently, there is little opportunity for product differentiation in the gypsum product industry.

In general, gypsum products are sold on a zone-delivered-price basis; each firm faces a downward sloping demand curve. Feedback mechanism from purchaser to producer is almost instantaneous, and any price cut by one firm is matched promptly by all others. It is not clear that a dominant price leader exists in the industry. A memorandum opinion in the case of Wall Products Company versus National Gypsum Company in the U.S. District Court of California (21) reported that several different firms initiated price changes during the late sixties.

The industry has been faced with problems of price wars when a firm makes price and other concessions in an attempt to add to its market share in a given region. When firms in the industry have taken steps to prevent further price deterioration, they have run afoul of antitrust legislation.

Lack of effective substitutes and the low cost of gypsum in relation to the final product indicate that demand in terms of price of gypsum or gypsum products is highly inelastic. That is, changes in the price of gypsum or gypsum products would have relatively little effect on quantity taken and changes in the price of crude gypsum would have even less effect on the quantity used for wallboard manufacture or in increasing sales of wallboard products. In terms of abatement market possibilities this would indicate that little expansion of gypsum sales would result from a general lowering of gypsum price levels. Abatement markets in the short run are developed only as a result of replacing crude gypsum that would be used in existing calcining plants. In time, new calcining plants may be built in association with utilities to serve markets that are distantly removed from existing plants.

Because of the inelastic nature of demand for gypsum products and the structure of the industry, it would be reasonable to assume that lower prices of abatement gypsum would not be passed on to the consumer of gypsum products as a result of its use by the existing industry. It may be further assumed that existing producers would purchase and use abatement gypsum at competitive prices even at the expense of their own mining operations rather than see it encourage new entrants to the industry. This reaction would be particularly true if relatively small quantities of abatement gypsum were to be produced.

Gypsum products are used in the building industry as an interior wall covering and in building shaft walls in high-rise buildings. It is one of a number of products that can be used in a building system. Today, most interior walls are made of wood framing and then covered with wallboard. This system is inexpensive relative to other construction methods. The gypsum product also has additional qualities of fire and noise resistance. Because of these qualities, over 90% of all interior walls are covered with gypsum products (27). Substitute systems for buildings are available; but when wood or metal framing is used, there are few substitutes for gypsum. Wood paneling and glass walls are substituted for gypsum products for aesthetic purposes where price is a minor consideration. Low-cost wood paneling has the disadvantage of lack of fire resistance which prevents its ability to substitute more fully for gypsum wallboard. When engineering and design specifications for interior walls call for wood or lightweight metal framing, there are few, if any, effective substitutes for gypsum wallboard covering.

Gypsum products make up a very small percentage of the total cost of construction. Although estimates of the cost of gypsum in today's average-value homes are not available, conversations with those associated with the industry indicate that gypsum costs amount to less than 1% of the total cost of the house. In high-rise buildings, the percentage would be even less. In 1974, total prefabricated products accounted for only 0.5% of the total value of construction. The value of the crude gypsum alone would be far less. Its value historically has been approximately 10% of the value of final gypsum products (Table 7).

TABLE 7. GYPSUM PRODUCTS, AVERAGE ANNUAL VALUE AT PLANT, AVERAGE VALUE CRUDE GYPSUM AT MINE, AND VALUE OF GYPSUM AS PERCENT OF PRODUCT VALUE - 1972 CONSTANT DOLLARS[a]

Year	Gypsum products per kft^2, \$ value	Crude gypsum per ton, \$ value	Gypsum value relative to product value, %
1956	58.30	5.14	8.8
1957	50.84	4.87	9.6
1958	51.17	4.94	9.7
1959	51.54	5.17	10.0
1960	52.54	5.13	9.8
1961	52.63	5.14	9.8
1962	53.51	5.04	9.4
1963	53.24	5.00	9.4
1964	52.58	4.89	9.3
1965	47.88	4.91	10.3
1966	47.75	4.74	9.9
1967	45.40	4.57	10.1
1968	42.87	4.38	10.2
1969	39.42	4.42	11.2
1970	33.65	4.02	11.9
1971	32.90	3.87	11.8
1972	35.09	3.93	11.2
1973	35.46	3.94	11.1
1974	36.40	3.80	10.4
1975	32.63	3.81	11.7

a. U.S. Bureau of Mines, Minerals Yearbook.

Use of wallboard products is highly dependent on the fortunes of the construction industry, in particular the residential building segment. As a result, the annual quantity demand is highly variable (see Figure 4). Annual use data are shown in Table 8.

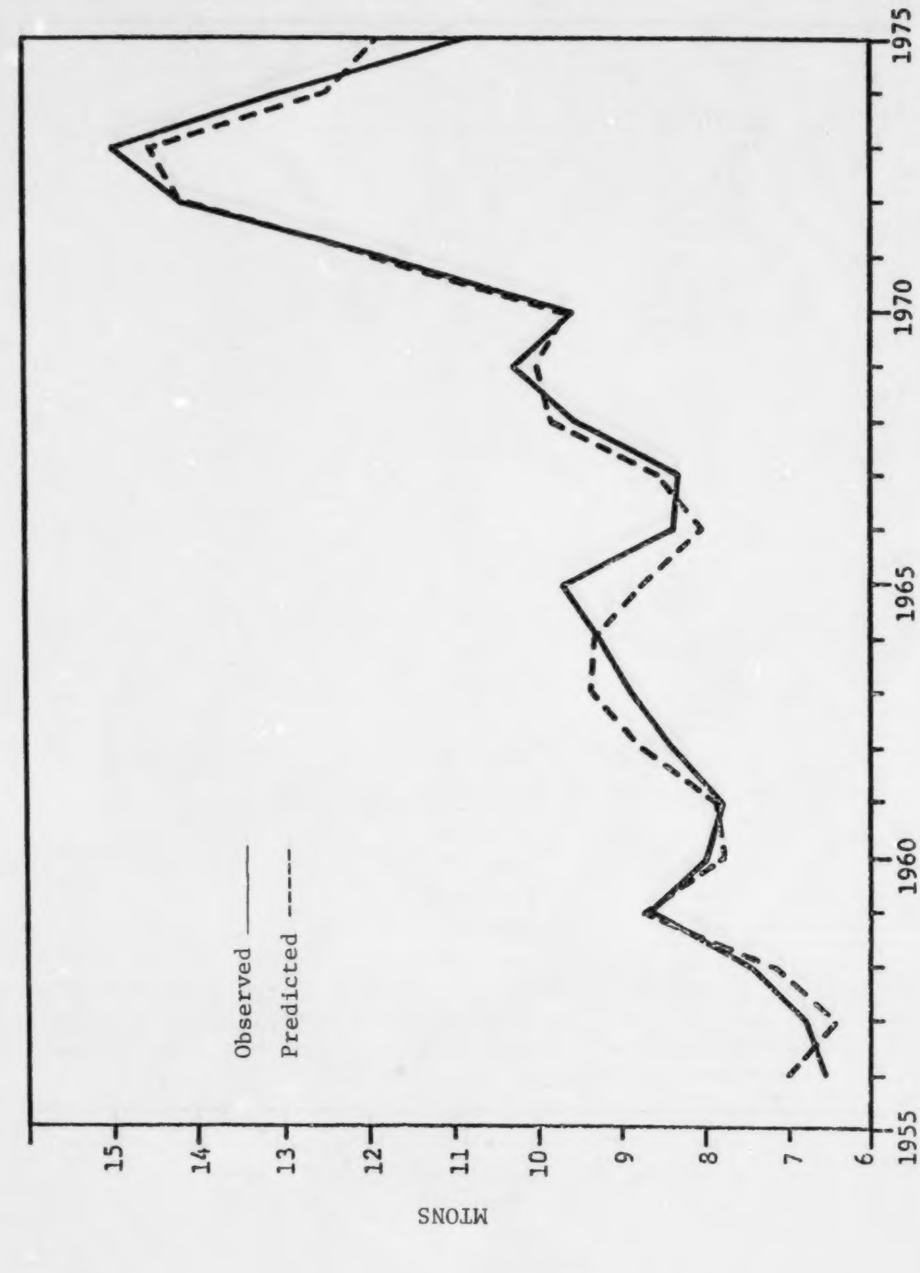

Figure 4. Observed and predicted consumption of wallboard products, 1955-1975.

TABLE 8. QUANTITY PREFABRICATED WALLBOARD PRODUCTS CONSUMED, VALUE OF CONSTRUCTION, AND RESIDENTIAL CONSTRUCTION AS A PERCENT OF TOTAL CONSTRUCTION

Year	Mft^2 wallboard products	Value construction, G\$[a]	Residential value as % total
1956	6,590,878	60.44	55.7
1957	6,771,889	57.18	52.9
1958	7,417,340	54.62	55.6
1959	8,688,903	60.59	60.4
1960	7,982,442	57.96	55.8
1961	7,808,342	57.30	55.2
1962	8,451,944	61.55	56.9
1963	8,906,272	63.30	58.1
1964	9,289,427	64.85	56.6
1965	9,721,452	69.51	51.6
1966	8,391,566	68.65	46.8
1967	8,280,657	65.95	47.2
1968	9,550,719	72.15	49.8
1969	10,282,383	76.24	48.8
1970	9,562,956	72.78	46.3
1971	11,889,927	83.18	53.0
1972	14,184,059	104.50	59.3
1973	15,004,025	109.06	57.6
1974	12,910,350	94.80	50.1
1975	10,742,008	80.41	48.0

a. Expressed in terms of constant 1972 dollars.

Gypsum products are supplied by calcining plants in response to demand in the construction industry. In 1975, 74 plants were in operation. These plants are strategically located to serve regional market demands and to minimize transportation cost. In major regional market areas, several firms may have calcining plants to serve those markets. Gypsum products essentially move from lowest cost supply points into markets. Calcining plants serving the interior of the country are located at gypsum mines and those serving coastal markets are located at seaports to use imported material at its lowest cost.

Demand at existing plants is quite variable on a year-to-year basis as shown in Table 9. This variability in use on a year-to-year basis will pose problems for both the utility and the calcining plants. The utility will be most interested in disposing of all its product, but it could not supply gypsum above that produced in meeting its power demands. If the utility is to develop arrangements for sale of its total abatement production on a year-to-year basis, flexibility would be required on the part of the purchaser. This flexibility would amount to a service to the utility which would involve an increased cost to the purchaser. If the utility does not make these arrangements, it must be prepared to stockpile its product to meet the fluctuations in demand. The utility has the option to stockpile unsold gypsum to be sold in future years.

TABLE 9. NUMBER CALCINING PLANTS, ANNUAL TONS GYPSUM CALCINED, AND AVERAGE PLANT USE, 1970-1975[a]

	1970	1972	1973	1974	1975
Number calcining plants	76	76	76	77	74
ktons					
Gypsum used by plants	9,153	14,217	14,917	12,841	9,885
Average use per plant	120	187	196	167	134

a. U.S. Bureau of Mines, Mineral Industry Surveys, 1970-75.

If abatement gypsum is to be produced on an economically feasible basis by a utility, it must develop its major market outlet through an existing calcining plant or its long-range planning might involve across-the-fence delivery of abatement gypsum to a new calcining plant. The existing gypsum products industry was built on the basis of existing supplies and markets. Manufacturing plants tend to be located in clusters. For example, there are seven plants located in south Georgia and north Florida. The next nearest cluster of plants is several hundred miles away. The locational phenomena precludes many utilities from a market for abatement gypsum through existing plants, but by the same token provides opportunities to supply new plants built specifically to use the abatement product.

CHARACTERISTICS OF CEMENT MARKET FOR GYPSUM

Gypsum is used in the cement industry to control the setting time of portland cement. While the amount of gypsum used per ton of cement varies depending on a number of factors, the industry average is about 5% by weight of the finished product (28).

The cement industry like the wallboard industry is closely tied to the level of construction activity. While there is some competition between cement and wallboard, they normally have different uses in construction. The cement industry is more closely linked to public works--highways, bridges, dams, and major construction--while the wallboard industry is more closely linked to residential construction activity. Domestic demand for cement is quite variable on a year-to-year basis and has shown annual variations of up to 5 Mtons. Domestic production has shown the same variability. Imports of cement have increased sharply since 1965.

Much of the recent increase in imports has been in clinker form. The imported clinker is then mixed with gypsum and ground into finished product. According to a recent Bureau of Mines publication (29), a part of the increased reliance on imports of clinkers may be attributed to stringent environmental regulations imposed in 1969. A number of kilns were closed due to the regulations and clinker was imported for distribution in the United States. From 1961 to 1969, imports of clinker amounted to about 10% of total imports but had increased to 41% in 1973. With declining use in 1974 and 1975, clinker imports dropped to 32 and 33% respectively.

The cement industry is an energy-intensive industry. According to the Bureau of Mines estimates, energy costs make up 40% or more of the direct costs of manufacturing cement. As a result of shortages and high prices of oil and gas, coal is now being considered as an alternative fuel source. New plants and plant expansions are geared toward larger capacity installations. This change may tend to increase gypsum requirements at specific locations as the industry adjusts to meet new economic conditions. However, the cement industry could supply a portion of its own demand for gypsum by producing abatement products from sulfur in coal.

Clinker may be stored outside for prolonged periods, but finished cement is perishable when exposed to moisture. Even if imports continue to increase, it appears that much of the increase will be in clinker form. If that is the case the domestic demand for gypsum will be based on the final demand for cement whether it is produced domestically or imported in clinker form.

The locations of existing and projected cement plants including grinding plants are shown in Figure 5. The average use of gypsum was over 23 ktons/plant in 1974 and the capacity of the industry was approximately 95 Mtons (30).

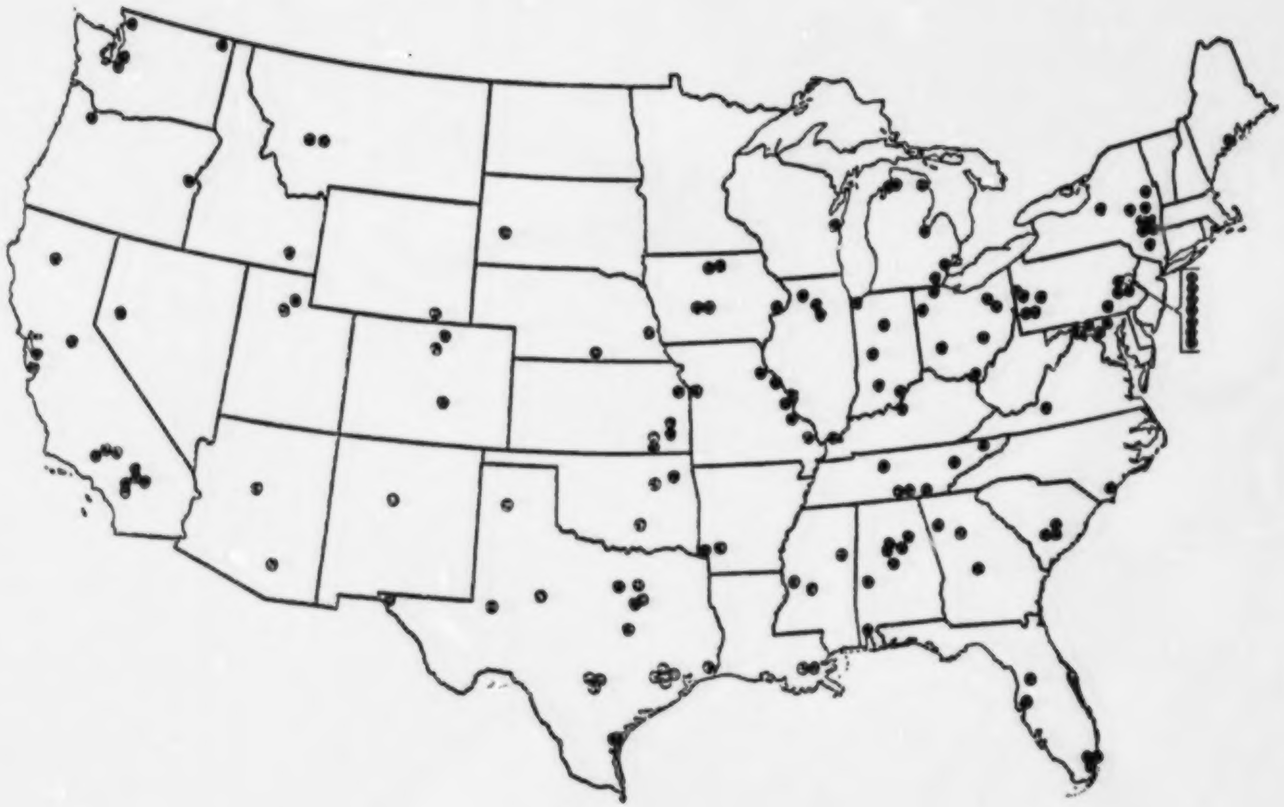

Figure 5. Location of domestic cement production plants, 1975 (Portland Cement Association).

Finish grinding capacity in the United States was approximately 103 Mtons and about 74% of capacity was used in 1974. In 1973, finish grinding capacity was approximately 97 Mtons and was operated at about 83% of capacity (31). The year of 1973 represented a record year for both production and consumption of cement in the United States. The average consumption of gypsum for each domestic cement plant was approximately 23 ktons. Data are not available to determine gypsum requirements for each cement plant, but capacity ratings should serve as a reliable guide. The Portland Cement Association has published a listing of all cement-producing plants in the United States that gives capacity and location information (32). This information will be utilized in developing specific demand points and quantities of gypsum demanded by the cement industry. The total projected capacity in 1978 is expected to be approximately 98 Mtons.

The Bureau of Mines recently published statistics (30) relative to the utilization of capacity by the cement industry. Portland cement statistics showing demand, production, prices, and imports between 1964 and 1975 are shown in Table 10. Between 1950 and 1974 capacity utilization has ranged between 72 and 92%. In twelve of those years utilization was between 70 and 80%. In seven years, utilization was between 80 and 90%; and in five years, utilization was greater than 90%. In this study it is assumed that the industry will operate at 85% of capacity as projected by the Portland Cement Association. It is further assumed that each plant will operate at 85% of capacity. The gypsum demand for a 500,000-ton/year cement plant would amount to 21,250 tons; 1% change in capacity utilization would result in a 250-ton/year change in demand for gypsum.

TABLE 10. PORTLAND CEMENT, U.S. DEMAND, PRODUCTION,

PRICES, AND IMPORTS - 1964-75[a] (29)

Year	U.S. demand, Mtons	U.S. production, Mtons	Mill value, $/ton	Imports, Mtons	Gypsum use in cement, Mtons
1964	68,865	69,303	16.98	683	2,986
1965	70,328	69,827	16.75	1,035	3,152
1966	71,570	72,311	16.59	1,328	3,372
1967	70,315	69,477	16.72	1,112	3,154
1968	74,720	74,243	16.80	1,370	3,439
1969	77,047	75,125	17.04	1,821	3,467
1970	73,407	73,168	17.69	2,579	3,358
1971	79,005	77,007	18.74	3,088	3,368
1972	81,432	80,744	20.31	4,911	3,924
1973	86,399	83,551	21.88	6,683	4,148
1974	82,917	79,486	25.62	5,732	4,058

CHARACTERISTICS OF AGRICULTURAL MARKETS

Gypsum use in agriculture, while showing an annual variation, has grown slowly. In 1965, 1.359 Mtons of gypsum were used, and by 1974, its use had grown to 1.671 Mtons. Agricultural use of gypsum has amounted to between 6 and 10% of the total annual use of crude gypsum during this period. Gypsum has two major uses in agriculture: (1) as a soil amendment on high-alkali soils that are reclaimed and irrigated, and (2) as a neutral source of calcium for peanut production. Other uses are to provide sulfur on sulfur-deficient soils and as animal feed additives.

The agricultural market for gypsum is centered in the Pacific region and more particularly in California. According to information from the Bureau of Mines, approximately 85% of the total agricultural use of gypsum is in that area. Primary agricultural uses are for soil-conditioning purposes in southern California, while in the northwestern coastal area where soils are deficient in sulfur, gypsum is used as a source of sulfur. Sulfur is a necessary plant nutrient, but, in the past, it has been a normal constituent of fertilizers. The fertilizer industry has changed to provide a high-analysis, sulfur-free product. Along with that change and the continuing increases in yields, sulfur deficiencies in crops have become a matter of concern in many areas of the country. Gypsum could be used to overcome those needs; however, the current trend appears to be to add sulfur to fertilizers to correct specific soil and crop problems when they are identified. Sulfur requirements for each acre are usually small. For example, most state extension services suggest that 10 pounds of sulfur for each acre of corn is adequate to provide sulfur when it is shown to be deficient. That amount of sulfur included in fertilizer permits its addition with only one application. If gypsum were used, an extra application step would be required. Both crude gypsum and gypsite are used for agricultural purposes, and in recent years byproduct gypsum from phosphatic fertilizer manufacturing has been used in increasing amounts. The Bureau of Mines recently began collecting and compiling data relating to the use of this source of byproduct gypsum in California. According to the 1974 Minerals Yearbook (13), three byproduct manufacturers supplied 463 ktons for agricultural use at a total value of $4.3M.

Gypsum is used in the Pacific region and elsewhere as a soil amendment on alkali soils. These soils contain excessive adsorbed sodium. Soil particles, because of negative electrical charges at their surfaces, adsorb cations, such as calcium, magnesium, and sodium. When sodium takes up 15% or more of a soils cation exchange capacity, it is termed an "alkali soil" (33).

Normally, calcium and magnesium are the major cations in the soil solution and on soil particles of productive soils. When these soils are irrigated with water containing sodium, this cation soon becomes excessive and alkali soils are formed. As a result, the rate at which plants can absorb water is reduced and plant growth is retarded. When alkali soils do not naturally contain gypsum, they must be leached with some form of soluble calcium or magnesium to restore them to normal productivity. (When sulfur is added, it hydrolyzes to sulfuric acid and hydrogen replaces sodium.)

Soil amendments may be of three types: soluble calcium salts (calcium chloride and gypsum); low solubility calcium salts (limestone); and acid or acid-forming compounds such as sulfur, sulfuric acid, iron, and aluminum sulfate (33). Because of their low cost and suitability, gypsum and sulfur are the most widely used soil amendments. Limestone is also inexpensive but is of little value except on acid soils. Most alkali soils already contain lime. Gypsum is also used as an addition to irrigation water containing soluble sodium salts.

While other soil amendments can be used, gypsum is the most widely used because of its suitability, availability, and low cost.

Although the principal agricultural use of gypsum is as a soil amendment on alkali soils, it also has important uses in peanut production. Peanuts require large amounts of soluble calcium in the soil surface to facilitate pegging and nut formation. Gypsum use is recommended when soil pH is already satisfactory, but additional calcium is needed (gypsum is a nonalkaline source of calcium). Typical recommendations range between 500 and 1000 pounds of gypsum per acre when needed.

Peanuts are grown in southern and southwestern states. Estimates of peanut production by states are shown in Table 11.

TABLE 11. PEANUT PRODUCTION BY STATES - 1974[a]

State	Acres
Alabama	198,500
Florida	55,000
Georgia	516,000
North Carolina	166,000
Oklahoma	228,000
Texas	576,000
Virginia	107,000
Total acres	1,843,500

a. Taken from estimates of acres grown by crops (data tapes from Statistical Reporting Service).

Due to the number of substitutes that exist for gypsum in agricultural uses, demand for this purpose should be more elastic than for construction uses. The Bureau of Mines has projected agricultural use of gypsum to increase from 1.450 Mtons in 1973 to 4 Mtons by the year 2000. The projection is based on the assumption that land will continue to be withdrawn from agriculture and that there will be a continued incentive to increase yields and to bring presently marginal agricultural land into productive uses. Alkali soils for which gypsum is particularly useful make up a significant portion of the marginal land that may be brought into more intensive use. These soils occur in the Western States which imply that the majority of increased use of gypsum will occur in that area (20).

The projected 4 Mtons for agriculture is approximately 11% of the total projected use of crude gypsum in the year 2000. This projection is consistent with the current agricultural share of total gypsum use.

Agricultural use of gypsum will continue to represent a significant market for gypsum in localized areas. Byproduct gypsum from fertilizer manufacturing operations is becoming an increasingly important source of supply of agricultural gypsum. The Bureau of Mines has only recently begun to collect data relative to quantities of byproduct gypsum used in agriculture. In addition to the quantities already reported used in California, it is known that byproduct gypsum is being supplied from fertilizer manufacturing firms in the South as well.

Data are not sufficient to establish quantity demands for agricultural gypsum by specific points to allow further study of agricultural markets within the methodology of this study. Agricultural markets are not included in the final market solution model used in this study.

GROWTH IN DEMAND FOR GYPSUM

Growth in demand for gypsum products is dependent primarily on growth in the construction industry. On a year-to-year basis, demand for gypsum has shown a great deal of variability, but over time there has been an upward trend in use. Table 12 characterizes growth in demand from 1965 to 1976 by major components.

The Bureau of Mines has recently published estimates of projected gypsum use by its major components. The projections were based on historical data through 1973. Total gypsum use by the year 2000 was projected to increase at an annual rate of 2%, and consumption was projected to fall within a range of 26 to 56 Mtons. Probable consumption was projected at 26 Mtons in 1985 and 34.8 Mtons in 2000. Projections compared with 1973, 1974, and estimates of 1975 and 1976 are shown in Table 13.

TABLE 12. GYPSUM USE BY MAJOR MARKETS, KTONS

Year	Total	Calcined products	Cement	Agriculture	Other
1965	16,092	11,137	3,152	1,359	444
1966	14,778	9,703	3,372	1,240	463
1967	14,132	9,274	3,154	1,280	424
1968	15,625	10,333	3,439	1,386	465
1969	15,818	10,763	3,464	1,100	491
1970	14,334	9,790	3,358	805	381
1971	16,914	12,028	3,386	1,124	376
1972	19,412	13,920	3,924	1,146	422
1973	20,636	14,565	4,148	1,453	470
1974	18,693	12,515	4,058	1,671	449
1975	15,588	10,390	3,244	1,482	N/A
1976	18,827[a]	13,574	3,308	1,314	N/A

a. Estimated from preliminary data. Source: A. H. Reed, "Gypsum." Bull. 667, U.S. Bureau of Mines, Table 3, p. 4.

TABLE 13. FORECASTS OF GYPSUM USE, KTONS

	1973	1974	1975[a]	1976[a]	Forecast range 2000		Probable	
					Low	High	1985	2000
Total use	20,636	18,693	15,588	18,827	25,800	55,500	26,000	34,800
End use								
Calcined products	14,565	12,515	10,390	13,574	18,000	40,000	N/A	20,000
Cement	4,148	4,058	3,244	3,308	6,000	10,000	N/A	10,000
Agriculture	1,453	1,671	1,482	1,314	1,000	4,000	N/A	4,000

a. Estimates from preliminary information. Source: U.S. Bureau of Mines preprint, Tables 6 and 7 (p. 7) and conversations with Bureau personnel for 1975 and 1976 estimates.

These projections indicate continued growth in demand for gypsum in its major uses--barring some completely unforeseen change in technology of construction. Such changes are unlikely because gypsum is widely available at a low cost. Gypsum products have a great deal of flexibility in use. They have distinct advantages over possible substitute products in fire and noise prevention in buildings. Gypsum products manufacturers actively seek to develop new uses and improve existing uses for their products. The development of gypsum board with special fire-retardant qualities and the greatly expanded use of wallboard and other gypsum products in high-rise structures are but two examples of many innovations made by the gypsum industry to expand uses for its products.

POTENTIAL NEW MARKETS

The Mobile Home Industry

The mobile home industry may develop as another major new use for wallboard products. Representatives of the Gypsum Association have indicated an expected increase in use of wallboard products by the mobile home industry as a result of recent changes in fire safety codes for mobile homes. Although it is much too early to quantify the impact of the mobile home market on total wallboard demand, the president of the Gypsum Association has indicated that he expects a market for approximately 1.5 Gft^2 of wallboard products to develop by 1985 when the production of mobile homes is expected to reach 600 kunits according to the projections released by the U.S. Department of Commerce (34).

Mobile home production is concentrated in 10 states that account for 75% of the 1972 production. These 10 states in order of total production were Georgia, Indiana, Texas, California, Alabama, Pennsylvania, Florida, North Carolina, Kansas, and Idaho. If the mobile home industry does begin to use wallboard products, it would represent significant new markets for the wallboard products in these states or localities.

New markets for wallboard products by the mobile home industry have not been accounted for in projections of national or regional demand. If such markets do develop, they would be in addition to estimates already made.

Agricultural Use of Gypsum Under Changing Conditions

The Sulphur Institute has recently published a series of technical articles dealing with potential sulfur needs in the United States. Potential sulfur requirements for the United States are summarized in Table 14. Total requirements amount to 2.5 Mtons of sulfur. This potential was based on calculated sulfur needs if crops grown in 1967 were fertilized according to recommended rates. Each geographical area in the United States was shown to need additional sulfur. Approximately

5.4 tons of gypsum are required to provide 1 ton of sulfur. If total sulfur requirements were supplied from gypsum, a total of 13.5 Mtons would be required. These projections of potentials are based on 1967 cropping patterns and recommended rates of fertilization (35). Undoubtedly, those potentials would be much higher if they were being projected to 1980 or 1985 conditions. Rapid increases in the use of nitrogen is one indication of growth in the potential need for sulfur. Agronomists consider the nitrogen to sulfur ratio in plants to be one of the major factors in projecting the sulfur potential. For each 10 pounds of nitrogen used by a plant, there must also be 1 pound of sulfur used. In 1976, the consumption of nitrogen in the United States amounted to 10.6 Mtons. TVA analysts project total nitrogen use in 1980 to amount to approximately 11.8 Mtons.

TABLE 14. POTENTIAL CONSUMPTION OF SULFUR AS A PLANT NUTRIENT IN THE UNITED STATES BY REGIONS AND EQUIVALENT GYPSUM[a]

Region	Intertilled and close-growing	Hay and pasture	Total crops	Equivalent gypsum
New England	8,358	15,298	23,656	127,742
Middle Atlantic	56,175	53,607	109,782	592,823
South Atlantic	110,886	97,933	208,819	1,127,623
East North Central	302,162	87,059	389,221	2,101,793
West North Central	436,480	312,484	748,964	4,044,406
East South Central	64,927	68,342	133,269	719,653
West South Central	149,681	194,720	344,401	1,859,765
Mountain	29,200	86,140	155,340	622,836
Pacific	88,014	332,105	420,119	2,268,643
Total	1,745,883	1,247,688	2,493,571	13,465,283

a. Source: "Potential Plant Nutrient Consumption in North America." The Sulphur Institute, Technical Bull. No. 16, Table 2, p. 23.

It is not suggested that this amount of sulfur will be applied directly by farmers or that all sulfur applied will use gypsum as the basic source. It only suggests that abatement gypsum in large quantities in many areas of the country could be used in a positive manner in agriculture as an alternative to throwaway processes.

The analysis of the demand for gypsum in agriculture indicates that use of gypsum would be responsive to lower prices. The indication that quantity used would increase significantly as a result of lower prices leads to an optimism that agricultural use of gypsum could be materially expanded for positive productive purposes by the combination of price reduction, time and place availability, and ease of application of the material.

Further work is needed to assess the practicality of the alternatives. To assure that a large amount of gypsum is used for agricultural purposes would require a decision at some level of government to subsidize the production and use of abatement gypsum to make it economically attractive to utilities and farmers.

The foregoing discussion of potential agricultural use of gypsum under a planned program to produce and utilize abatement gypsum in lieu of throwaway sludge suggests the need for further consideration. Initial evaluation from an agronomic and economic viewpoint under varying assumptions of SO_2 emissions, cropping practices, and price relationships of other sulfur sources is suggested.

Projected Gypsum Use - 1978

This study focuses on 1978 conditions projected by the utility industry as the base year for the study. Markets for byproducts for the year 1978 are estimated that give an indication of supply-demand conditions facing the utility in that year. Maximum consumption of gypsum occurred in 1973 when 20.6 Mtons was used. Use dropped sharply through 1975 down to 15.6 Mtons reflecting the depressed state of the economy in general and the construction industry in particular. Use was estimated at 18.8 Mtons in 1976. It appears that gypsum consumption in 1978 or shortly thereafter will equal the 1973 level of over 20 Mtons. In that year, 14.565 Mtons was used in calcining plants, 4.1 Mtons in cement use, and 1.4 Mtons was used in agriculture. This figure provides a conservative estimate upon which to base long-range planning. Estimates of use in cement are actually based on an assumption of 85% of actual capacity projected by the cement industry for 1978. This amounts to 4.042 Mtons compared to 1973's use of 4.148 Mtons.

An annual growth rate of 2% or less each year does not represent a rapidly growing demand, but continued growth in demand seems assured. This factor is probably of more interest to the utilities since their strategy would have to be based on replacing crude gypsum in its present uses rather than developing new markets.

Within that strategy replacement of imported materials appears the most viable prospect. Reference to Table 15 shows the magnitude of imports each year since 1955. Imports typically account for 37-40% of the total domestic gypsum use. While f.o.b. mine prices are lower in general than in the United States, the added transportation cost makes this gypsum slightly higher in price giving more of an opportunity for abatement producers to develop this market. Prices on imported materials have increased from $2.24/ton in 1970 to $2.94/ton in 1975 for an increase of 31%. Prices in the United States during the same period increased from $3.72 to $4.80/ton for an increase of 29%. Further, to the degree that rail rate increases of approximately 70% may be reflected in the costs of water transportation, one could expect transportation costs for imported gypsum to continue to increase even more rapidly than mining costs. This could result in additional opportunity for abatement product to replace imported material.

TABLE 15. GYPSUM USE, PRODUCTION, AND VALUE - 1955-75[a]

Year	Domestic use, ktons	Domestic production, ktons	Average value f.o.b., $/ton	Imports, ktons	Average value f.o.b., $/ton
1955	13,994	10,684	3.18	3,966	1.58
1956	13,676	10,316	3.31	4,336	1.80
1957	12,720	9,195	3.25	4,334	1.75
1958	13,210	9,600	3.38	4,049	1.70
1959	15,200	10,900	3.59	6,135	1.94
1960	14,008	9,825	3.63	5,301	1.70
1961	13,692	9,500	3.68	4,967	1.82
1962	14,514	9,969	3.65	5,421	1.94
1963	15,155	10,388	3.67	5,490	1.98
1964	15,879	10,684	3.64	6,258	2.13
1965	16,092	10,033	3.73	5,911	2.37
1966	14,778	9,647	3.70	5,479	2.37
1967	14,132	9,393	3.66	4,563	2.87
1968	15,625	10,018	3.67	5,474	2.08
1969	15,818	9,905	3.88	5,858	2.12
1970	14,334	9,436	3.72	6,128	2.24
1971	16,914	10,418	3.75	6,094	2.21
1972	19,412	12,328	3.93	7,718	2.38
1973	20,636	13,558	4.18	7,661	2.30
1974	18,693	11,999	4.41	7,424	2.37
1975	15,190	9,251	4.80	5,448	2.94

a. U.S. Bureau of Mines, Minerals Yearbook.

New Plant Locations

The analysis based on projected 1978 conditions is essentially a "short-run" demand study in that it assumes demand points are fixed. If new locations could be established, more utilities might be considered potential gypsum producers. The analysis did not consider long-run aspects as they relate to possible across-the-fence wallboard manufacturing plants, except to list potential supply points. Substantial additional work, including analysis of end product markets would have to be done to adequately cover this possibility.

Data are available to compare production of calcined gypsum products with consumption on a regional basis since 1970. These data indicate rather stable consumption patterns over time and lead to the conclusion that regional markets as a percentage of total markets can be expected to remain quite stable. These data are shown in Table 16. Development of the industry around existing sources of raw materials and markets has resulted in overproduction in some regions and underproduction in others. This provides an opportunity for calcining plants to be built across-the-fence from utilities that would supply their gypsum requirements. The inland areas of the Southeast are the most obvious potential new locations. Reference to figures showing mine and plant locations indicates the entire southeastern area is served from fringe points.

TABLE 16. REGIONAL CONSUMPTION WALLBOARD PRODUCTS AND PERCENT OF TOTAL U.S. CONSUMPTION, COMPARED TO REGIONAL PRODUCTION, 1975[a]

	Consumption, kft^2					Regional production
	1971	1972	1973	1974	1975	% of U.S., 1975
Consumption, states						
New England	599,733	714,143	754,487	635,863	539,959	
% of U.S.	5.0	5.0	5.0	4.9	5.0	2.8
Middle Atlantic	1,445,695	1,675,887	1,833,551	1,575,276	1,257,871	
% of U.S.	12.1	11.7	12.1	12.3	11.6	17.1
East North Central	1,899,212	2,195,527	2,286,213	1,934,285	1,694,319	
% of U.S.	15.9	15.3	15.1	15.0	15.7	16.7
West North Central	816,100	960,787	982,728	890,239	858,964	
% of U.S.	6.8	6.9	6.5	6.9	8.0	9.8
South Atlantic	2,183,400	2,799,276	3,148,819	2,650,507	1,763,458	
% of U.S.	18.3	19.5	20.8	20.6	16.3	14.3
East South Central	689,796	845,511	872,981	741,168	615,576	
% of U.S.	5.8	5.9	5.8	5.8	5.7	-
West South Central	1,601,927	1,950,459	1,863,788	1,505,508	1,457,730	
% of U.S.	13.4	13.6	12.3	11.7	13.5	20.7
Mountain	811,121	1,077,558	1,142,407	909,993	797,983	
% of U.S.	6.8	7.5	7.5	7.1	7.4	8.8
Pacific	1,863,795	2,100,962	2,199,509	1,875,903	1,693,335	
% of U.S.	15.6	14.6	14.5	14.6	15.7	9.8

a. U.S. Bureau of Mines. "Sales of Gypsum in the 4th Quarter."

METHOD OF ANALYSIS OF ABATEMENT GYPSUM MARKET POTENTIAL

General conditions of supply and demand, growth potentials, and characteristics of individual markets, along with observations concerning entry conditions have been presented. In addition, projections of national demand for gypsum for use in the wallboard (calcining plants) and cement markets have been developed in the previous section. These projections will be used in the market solutions to be developed. The analysis also includes possible across-the-fence new calcining plants to be built to serve existing markets by utilizing abatement gypsum. The analysis will determine if there are possible points where abatement gypsum might be lower in cost than crude gypsum from existing supply points at given prices.

DATA BASE DEVELOPMENT

Gypsum has been shown to be a low-cost product that must be used near the point of supply because transportation cost quickly becomes a major part of product value. Location of potential abatement production by utilities with respect to existing supply and demand points becomes an extremely important factor in determining the feasibility of abatement production. It is necessary to determine specific information concerning each demand and supply point. In regard to demand, each calcining plant receives its supply of crude gypsum from specific integrated mines. Those specific supply-demand points were identified. The cement industry and individual cement plants are not so integrated and are assumed to obtain their crude gypsum requirements at the lowest delivered costs from any suitable supplier of crude gypsum. Specific quantity requirements at each demand point of calcining or cement plant were determined and supply prices and conditions were estimated. The delivered cost of crude gypsum was calculated for each demand point. For abatement gypsum to replace crude gypsum at demand points, it must be available at the demand point at a lower price.

The ability of utilities to supply the demand depends on their location and relative cost of scrubbing by a gypsum-producing process compared to the cost of scrubbing by a disposal process or by using clean fuel. It is assumed that the gypsum process would only be used when revenue from the sale of gypsum to the preceding described market would result in adequate revenue to offset the cost difference between lower cost processes and the gypsum process.

After developing demand and supply data bases, costs of scrubbing by alternative processes for each utility not in compliance were developed. After scrubbing costs were developed, market solutions were generated based on supply-demand conditions, scrubbing costs, and transportation costs utilizing a modified linear-programing transportation model.

The study is made on the basis that each utility operating in 1978 must be in compliance with air quality laws and regulations effective July 1, 1976. If a plant is out of compliance, it must undergo changes that involve cost to continue operation. For purposes of this study, the plant is allowed to choose among four alternatives: (1) the plant may scrub by the limestone slurry disposal process, which is the lowest cost process available and is used as the standard from which other costs are based, (2) the plant may scrub by the gypsum process, which results in wallboard quality gypsum that has market value, (3) exclusive use of low-sulfur fuel (because of age and size of some boilers in operation, scrubber installation would result in extremely high cost--to overcome this, a clean-fuel cost parameter was used to provide an alternative to scrubbing.), and (4) the use of low-sulfur fuel in some boilers and an FGD system installed on other boilers at the same plant.

The cost under alternative (1) is viewed as the minimum cost required to continue operation. The plant would choose the gypsum process only if the total control cost including net revenue f.o.b. plant from sale of gypsum is equal to or less than the cost under alternative (1) that includes all costs of disposal. If revenue from gypsum sales exceeds the cost difference, then the plant would actually lower its cost of meeting compliance regulations. If revenue just equaled incremental cost, no savings would be realized, but problems associated with disposal would be eliminated.

Short-Run Demand

The previous discussion of characteristics of demand for gypsum in each of its major markets has established that the demand for gypsum in the construction and cement industries is independent of price. Also, in both the construction and cement industries demand is concentrated at relatively few points. Seventy-four calcining plants manufacture all the prefabricated products used by the construction industry. In 1974 these plants used 12,841 ktons of crude gypsum for an average of over 170 ktons/plant. The cement industry used an average of over 23 ktons of crude gypsum per plant.

A 500-MW power plant using 3.5% sulfur coal would produce approximately 240 ktons of abatement gypsum on a dry basis when 90% of the sulfur is recovered. Because of transportation costs and the location of supply and demand points, abatement gypsum must be marketed near the point of production if it is to be economically feasible. Because of the inelasticity of demand for gypsum, it was assumed that the quantity demanded will not increase as a result of the manufacture and sale of abatement gypsum.

A discussion of how the various demand and supply data bases were developed and how they are used in the analysis follows.

Calcining Plants

In order to utilize the analytical model to arrive at market solutions, it is first necessary to estimate the tonnage of crude or abatement gypsum that will be consumed at each calcining plant under any assumed level of domestic consumption.

The data base for 1978 is based on plants that were in operation in 1975 as listed by the Bureau of Mines (36). Of the 74 plants in operation in 1975, the Bureau of Mines listed the following top 10 in order of production:

1. U.S. Gypsum's Plaster City plant in Imperial County, California
2. U.S. Gypsum's plant in Martin County, Indiana
3. U.S. Gypsum's Stoney Point plant in Rockland County, New York
4. U.S. Gypsum's Southard plant in Blaine County, Oklahoma
5. National Gypsum's Shoals plant in Martin County, Indiana
6. U.S. Gypsum's Fort Dodge plant in Webster County, Iowa
7. Weyerhaeuser's Briar plant in Howard County, Arizona
8. Georgia-Pacific's Acme plant in Hardeman County, Texas
9. National Gypsum's Savannah plant in Chatham County, Georgia
10. U.S. Gypsum's Jacksonville plant in Duval County, Florida

These 10 plants accounted for 27% of the total production in 1975. A commercial data service (37) also lists many of the gypsum plants showing total sales, employment class, and sales at each listed plant as a percent of total industry sales. Using these sources of information, it was possible to develop estimates of sales at each plant as a percentage of total industry sales. The percentages used were checked against other information. First, the 10 leading plants had to equal 27% of the total production. Second, imported material for the past 3 years has amounted to 37-40% of the total use. It was assumed that plants using imported material would account for approximately that percentage of the total industry sales. Third, the concentration ratio of the top four firms has consistently been about 80%. The percentages used meet these three checks and, of course, represent 100% of the total production. The percentages at each plant were then used to calculate tons of gypsum required at each demand point (calcining plant) based on estimated industry requirements for 1978.

Based on the above analysis, the percentage of the national market estimated for each calcining plant ranged from 0.3 to 3.5%. The percentage estimated for each plant is multiplied by the estimated total industry demand to provide an estimate of crude gypsum demand at each calcining plant. The national market for 1978 for gypsum use in calcining plants is projected at 14.565 Mtons.

This procedure for estimating short-run gypsum demand at each plant undoubtedly tends to minimize differences in production levels at given plants but should, nevertheless, give a good order of magnitude estimate of quantity needed at each production point. Year-to-year variation in sales would likely create a greater error in the estimated requirements at a particular plant than the error in estimating the percentage of national sales from a given plant for a given year.

There are obvious shortcomings to the method used to determine gypsum requirements at each calcining plant, but with the available data, this approach seems the most feasible. Since calcining plants tend to be clustered, errors at each plant tend to be averaged, and total requirements for a group of plants in a production area would tend to more accurately reflect quantity demanded in a given region with comparable delivered costs of crude gypsum and alternative costs of abatement gypsum.

New Plant Locations

Plant production and sales as a percentage of national sales would be expected to vary because of production problems at a particular plant and over a longer period of time due to shifts in demand for final product among market locations. For example, the relative growth in economic activity in the South and Southwest would be expected to cause the demand for gypsum products to increase in those regions and decrease or at least slow in rate of growth in other regions. As these changes take place it is assumed that the plants located nearest to growth areas would tend to increase sales in both absolute and relative terms until new plants were built in growth areas to meet the increased demand. If data were available on a state basis, some of these changes might already be evident. Data are available on a regional basis and are shown in Table 16. These data indicate a rather constant relative demand for gypsum products among census regions. The South Atlantic region is the only region that indicates a relative decline and the West North Central and Mountain regions indicate minor relative increases.

Shifts in demand for gypsum products between regions have occurred, but these shifts have occurred rather slowly. This trend supports the assumption that, while absolute levels of production vary at individual plants based on change in the construction industry, relative production at individual plants would tend to be less variable.

Possible new across-the-fence calcining plants were assumed to have a minimum demand of 200 ktons gypsum (equivalent to about 500 MW of abatement production) which is consistent with known information relative to the economical size of plants.

CEMENT PLANT DATA BASE

The Portland Cement Association published a booklet listing all cement-producing firms and plant locations and capacities in 1975. The publication also listed all announced planned changes in capacity through 1979. The total capacity in 1975 was 95,112 ktons. Net planned changes through 1978 add 2,792 ktons to the present making a total capacity of 97,904 ktons.

This study assumes 85% of the projected industry capacity will be utilized by 1978. The data base in this study is based on the assumption that each plant in the industry operates at that level of capacity. In other words, the computer program is designed to multiply the listed capacity by a constant percentage to estimate cement production at a given plant location. Gypsum requirements are also assumed constant at 5% of cement.

The data base can be overridden to change either of the percentages used in this analysis or to directly insert gypsum requirements at each calcining and cement plant location, if known.

Supply

Existing mine locations are shown in Figure 6. In a previous section it was noted that reserves and mine locations served major interior markets for gypsum and gypsum products but that economic reserves do not exist to serve major markets in coastal areas of the United States. These markets are served by importing crude gypsum from mines in Nova Scotia and Mexico. Typically, about 35-40% of the requirements in the United States are imported annually. The Canadian mines are by far the most important source of imported crude gypsum. Imported material comes from mines located at or near the sea, and in many cases it is loaded directly into ocean-going ships of up to 30-kton capacity for shipment to domestic calcining plants that are equipped to off-load directly into storage (38). In addition to manufacturing the full range of gypsum products, these calcining plants also serve as distribution points for shipping uncalcined gypsum to other users.

To summarize, gypsum markets may be supplied by crude gypsum that is either mined domestically or imported. In addition, agricultural markets may be supplied by gypsite mines and by byproduct gypsum from phosphatic fertilizer manufacturing operations. Also, calcining plants located in seacoast towns are considered supply points for cement and agricultural markets since they serve as distribution points for imported material in addition to performing their manufacturing operations. Of course, each utility out of compliance is also considered a potential supply point.

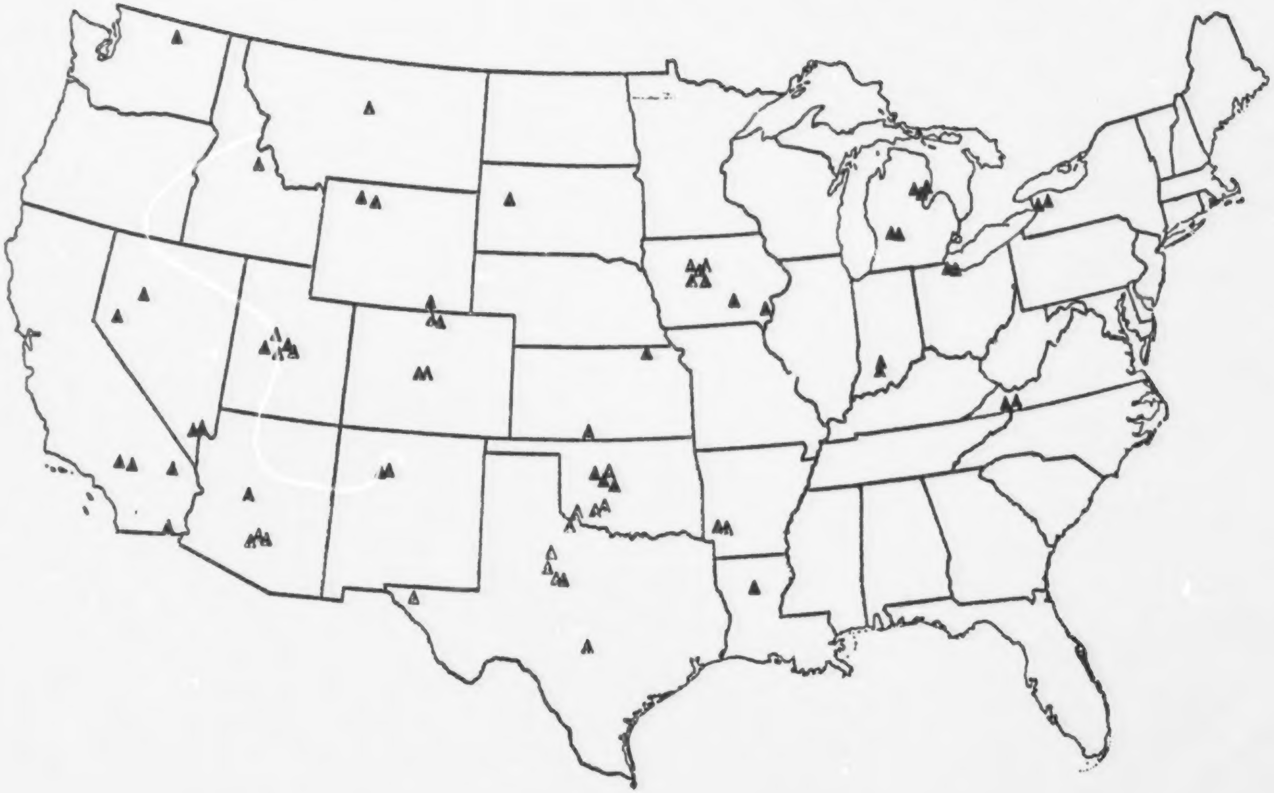

Figure 6 . Location of domestic gypsum mines, 1975 (Mineral Industry Surveys).

Since each calcining plant obtains its gypsum requirements from a given integrated mining operation (supply point), a fixed supply point has been designated for each calcining demand point. In the model no other crude gypsum supply point is allowed to supply a given calcining plant; only abatement gypsum can compete. Cement plants, on the other hand, may be supplied by any gypsum supplier.

Supply Prices

It is impossible within the scope of this study to estimate mining costs on an individual mine basis or on a regional basis. It has therefore been necessary to use average values for gypsum as reported by the Bureau of Mines. It is known that calcining plants are supplied by integrated mines but that most cement plants do not have integrated sources of supply. There is little precedent upon which to draw to anticipate how gypsum producers would react to lower cost alternatives, other things being equal. The utility will prefer to dispose of his total product to avoid the problem of stockpiling. Because of the quantities of product involved, a calcining market is almost a necessity for the utility if it is to avoid stockpiling. If the gypsum industry negotiates for an abatement product only at its lowest mining cost, it will reduce average revenue per ton that the utility might realize. If the revenue anticipated by the utility is not sufficient to offset its cost difference, the utility will not undertake the gypsum process. This also has the effect of removing the utility from competition for other existing markets.

There may be at least one exception to this line of reasoning. Earlier, it was suggested that entry into the wallboard products manufacturing industry was effectively blocked, especially in the Eastern States, by absolute costs. Abatement supplies would significantly alter this picture. It is possible that current integrated gypsum producers might actively bid for an abatement product in order to retain its market share in a given area and maintain existing prices.

What may occur can only be conjecture. For purpose of the study on a national basis it will be assumed that utilities must compete for calcining markets at the lower cost alternatives that have been presented. The supply data base, therefore, provides internal and external price fields. Supply prices of crude gypsum to calcining plants, all of which are integrated, will be based on internal prices. The internal price reflects estimated variable cost of mining. Supply prices for cement plants are based on the external or market price. All prices are f.o.b. supply point and appropriate transportation cost is calculated from supply to demand points. The lowest delivered cost under conditions described becomes the cost with which abatement product must compete.

Specific supply prices for crude gypsum to be used in the analysis are based on current information from the U.S. and Canadian Bureau of Mines. Internal prices are based on an approximation of variable mining cost and external prices based on the reported average value per ton sold to the cement market. The initial prices to be used are based on conservative estimates of prevailing cost. If the analysis based on conservative cost estimates justifies additional work, market solutions may be developed by increasing price levels for both internal and external prices.

According to information presented in a previous section the variable cost of mining crude gypsum in Canada is estimated at $1.42/ton. Movement to ports and loading onto cargo ships would be added cost to be considered in estimating an f.o.b. price for imported material. Based on this information a minimum price f.o.b. Canada and other import sources is established at $2.00/ton and the maximum price is $5.00/ton. Domestic mining costs vary widely but appear to be somewhat greater than mining cost in Canada due to differences in quality of mines and higher labor costs in the United States; internal prices f.o.b. domestic mines are assumed at $3/ton minimum and $6/ton maximum.

External prices are based on average value per ton of gypsum sold in the cement industry as reported by the Bureau of Mines. In 1974 that figure was $5.94/ton (Table 17). A minimum external f.o.b. domestic mine supply point price of $6.00/ton and a maximum price of $10.00/ton are used. Calcining plants using imported materials also serve as supply points for nearby cement and agricultural markets. External prices from these supply points will be based on internal price f.o.b. Canada, plus transportation cost, plus $2.00/ton handling charge.

No representation is made that these prices are definitive, but it is felt that the range of prices used is indicative of the price situation that utilities would have to meet in order to market abatement gypsum. The prices used should provide a good indication of the potential for abatement gypsum production by the industry. The decision to produce gypsum is an individual plant, not an industry, decision and the information specific to that firm will be used in making the decision.

After f.o.b. prices are determined, appropriate transportation cost is calculated to arrive at delivered cost of crude gypsum to each demand point. All cement plants are assumed to receive gypsum requirements by rail from either mines or utilities. Point-to-point mileage is calculated through the use of a computer program (standard point location code). In the case of imported material and mines located on the Great Lakes that deliver crude gypsum to calcining plants, rates were not available. Water transportation rates were assumed at $3.00/ton as far south as Norfolk, Virginia; $4.00/ton to south Florida; and $5.00/ton to Gulf and Pacific Coast locations. Since abatement gypsum contains approximately 20% free moisture as compared with approximately 3% free moisture in crude gypsum, it is necessary to add 17% to the cost of rail transportation of abatement gypsum to equalize transportation costs.

TABLE 17. GYPSUM USE AND VALUE BY MAJOR CONSUMING SECTOR[a]

Year	Calcined, ktons	Average value, $/ton	Cement, ktons	Average value, $/ton	Agriculture, ktons	Average value, $/ton
1955	10,437	3.18	2,226	3.92	678	3.39
1956	9,820	3.31	2,394	4.02	830	3.37
1957	9,019	3.25	2,273	4.21	830	3.76
1958	9,227	3.38	2,416	4.23	1,021	3.30
1959	10,657	3.59	2,757	4.30	1,188	3.09
1960	9,797	3.63	2,543	4.42	1,126	3.29
1961	9,360	3.68	2,763	4.27	1,088	3.50
1962	10,035	3.65	2,765	4.47	1,241	3.40
1963	10,519	3.67	2,898	4.46	1,262	3.46
1964	10,326	3.64	2,986	4.52	1,270	3.52
1965	10,112	3.73	3,152	4.62	1,265	3.68
1966	9,826	3.70	3,372	4.62	1,276	3.96
1967	9,313	3.66	3,154	4.66	1,280	4.27
1968	10,391	3.67	3,439	4.66	1,388	4.48
1969	10,861	3.88	3,464	4.58	1,100	4.85
1970	9,953	3.12	3,358	4.74	804	5.27
1971	12,291	3.75	3,386	4.78	1,124	4.79
1972	14,217	3.93	3,924	4.94	1,146	5.21
1973	14,917	4.18	4,148	5.35	1,453	5.09
1974	12,841	4.41	4,058	5.94	1,671	7.62
1975	10,390	4.51	3,244	6.25[b]	1,482	8.00[b]

[a] U.S. Bureau of Mines, Minerals Yearbook.

[b] Estimated.

FGD COST COMPARISONS

Three gypsum-producing FGD systems, limestone-gypsum, Chiyoda Thoroughbred 101, and Dowa aluminum sulfate, were chosen to be evaluated in this study. Desulfurization costs for each of the three systems are estimated and compared using simulated base case conditions. Also, costs for the limestone slurry throwaway system originally developed by TVA (9) are updated to the same base conditions. Investment and average annual revenue requirements are projected for each system, including limestone slurry, from base case premises. Nine other gypsum-producing processes are mentioned briefly as potential alternatives for gypsum production from FGD. The description of gypsum-producing systems and the evaluation of four FGD systems are interesting in themselves as a technological and economic comparison of alternative FGD methods.

Lifetime revenue requirements for the limestone slurry and limestone-gypsum processes are calculated by use of a computer program developed by TVA (39). These costs are used for the marketing portion of the study.

To discuss and compare FGD processes, it is necessary to define a common basis for reference. The base case established for this report is used to determine investment costs and revenue requirements for the four FGD processes listed above. Design conditions have been assumed so that all processes have common basis for technical comparison. Elements used in designing the base case are chosen because they represent typical average conditions of the more modern boilers for which stack gas desulfurization is most likely to be considered.

DESIGN PREMISES

Attention is focused on coal-burning power units for two reasons: (1) coal will be the major fuel source for the next several years as fuel oil and natural gas prices increase because of decreasing supplies, and (2) coal, in comparison to other fossil fuels, is the source of greatest pollution because it contains more ash, sulfur, chlorides, nitrogen oxides, and trace elements which must be removed and disposed of. Low-sulfur coals containing less than 0.8% sulfur are one answer to SO_2 emission control but they are often unavailable or economically unfeasible. A wide variety of coals, with sulfur ranges from a few tenths of a percent to 5% or greater, will continue to be used in the future for the production of electricity in this country. The coal assumed for the base case in this study is bituminous, contains 3.5% sulfur and 12% ash, and has a total heating value of 12 kBtu/lb.

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Coal-fired power plants are being built today in sizes up to 1300 MW, but older units of 200 MW and smaller will continue to be operated for many years. The base case power plant is defined for this study as a new 500-MW unit with a heat rate of 9 kBtu/kWh and an annual capacity of 7 kkWh/kW. The assumed operating life of a new coal-fired power unit is 30 years. A power plant operating schedule has been assumed for the base case of this study which represents a total on-stream time of 127,500 hours over the plant life. Lifetime revenue requirements are projected from this schedule which is shown in Table 18. This capacity schedule corresponds to that which was used in the TVA cost study (9).

TABLE 18. ASSUMED POWER PLANT CAPACITY SCHEDULE

Operating year	Capacity factor, % (nameplate rating)	Annual kWh/kW capacity
1-10	80	7,000
11-15	57	5,000
16-20	40	3,500
21-30	17	1,500
Average for 30-year life	48.5	4,250

Design premises for this report follow those outlined in TVA's detailed cost study of five processes (9). A balanced-draft boiler design is assumed. Flue gas composition is based on combustion of pulverized coal with 20% excess air to the boiler and 13% additional air inleakage at the air preheater. The following flue gas composition from the boiler is used for the material balance.

Flue gas composition	Vol, %
Nitrogen	74.55
Carbon dioxide	12.55
Oxygen	4.86
Water	7.76
SO_2	0.22
Nitrogen dioxide	0.06
Fly ash loading	
Gr/sft^3, dry	4.11
Gr/sft^3, wet	3.79

It is assumed that 92% of the sulfur present in coal is emitted as SO_2 and 75% of the ash is emitted as fly ash. Particulate removal is carried out by electrostatic precipitators (ESP) designed for a removal efficiency of 99.5%. A 500-MW power unit is assumed to have four economizers, air heaters, ESP, ducts, and ID fans.

The fan is designed to overcome a pressure drop of about 15 inches downstream of the boiler plus the additional pressure drop attributed to SO_2 removal. Fully sized ID fans are included in the equipment list, but costs for an equivalent 15-inch ID fan is subtracted from the total cost as a boiler charge. Only costs for the incremental increase in fan capacity needed by the addition of SO_2 removal is charged to the removal process.

Proven design, not first-of-a-kind, is assumed for each system evaluated and 90% SO_2 removal in the absorber is assumed for each case. Bypass ducts for maintaining full power generation capacity during shutdown of one or more scrubbing trains are not provided.

Stack gas reheat downstream of the absorber is required for plume buoyancy. Cleaned gas exits the scrubber at about 125°F and is heated by indirect steam reheaters before entering the fans. Heat of compression is added by the fans and the gas enters the stack at 175°F. Additional steam is provided to account for heating and evaporation of entrained liquid in the gas.

Raw materials used in the four detailed processes are listed below.

1. Limestone

    Purchase size: 0 x 1-1/2 inches
    Analysis: 90% $CaCO_3$ (dry), 5% H_2O

    Limestone ground as 60% solids slurry
      Ground size: 70% minus 200 mesh
      Bulk density: 95 lb/ft^3
      Storage capacity: 30 days

2. Sulfuric acid

    Analysis: 98% H_2SO_4
    Specific gravity: 1.831
    Storage capacity: 60 days

3. Ferric sulfate

    Analysis: 20% trivalent iron
    Bulk density: 60 lb/ft^3
    Storage capacity: 15 days

4. Aluminum sulfate

    Analysis: 50% $Al_2(SO_4)_3$
    Bulk density: 50 lb/ft^3
    Storage capacity: 15 days

5. Manganese sulfate

    Analysis: 28% manganese
    Bulk density: 70 lb/ft^3
    Storage capacity: purchased in bags

Total land requirement for each process, excluding waste solids disposal and gypsum stockpiling areas, is 9 acres. The limestone slurry process from the TVA cost study (9) includes onsite disposal of waste calcium solids. Adequate land is purchased initially to provide ponding for the life of the plant. For the base case (new unit, 30-year operating life) a 206-acre common disposal pond, 40 feet deep and clay lined, is required for calcium solids and fly ash. Based on relative volume, 131 acres of the pond is charged to SO_2 removal. The gypsum-producing processes are assumed to require 9 acres of land for temporary stockpiling of the abatement gypsum.

COST PREMISES

Because of the concentration of coal-fired power plants and the abundance of coal fields in the Midwestern States, this study assumes a Midwest location for the power unit described. Land costs are assumed at $3500/acre. Project design is assumed to begin in mid-1975 and construction is assumed complete in mid-1978. Average cost basis for scaling is mid-1977. Investment costs for each system start at the plenum which feeds the absorbers; the cost of particulate removal is not included in the study.

Direct investments are prepared using the following Chemical Engineering cost indices and projections (40).

Year	1974	1975	1976[a]	1977[a]
Material	171.2	194.7	210.3	227.1
Labor	163.3	168.6	183.8	200.3

a. Projections.

Included in direct investment are equipment, installation, labor and materials, land, utilities, services, and construction facilities. In the limestone slurry and limestone-gypsum processes, detailed analysis of the utilities and services areas has been made to project costs for such items as piping, wiring, and process equipment. For the Chiyoda and Dowa processes, process areas and land investment costs are totaled and utilities and services are estimated as 0.5% and 5.0% of this cost respectively. For all four processes, subtotal costs for equipment and field materials for each process area and land, utilities, and services are summed and construction facilities are estimated as 5% of this subtotal.

Indirect investment includes engineering design and supervision, construction field expense, contractor fees, and contingency. These are estimated as a percentage of direct investment according to the following list.

Indirect investment cost	Percentage of direct investment
Engineering design and supervision	9
Construction field expense	11
Contractor fees	5
Contingency	10
Total	35

Allowance for startup and modification and interest during construction are each estimated at 8% of the fixed investment. A capital structure of 50% debt - 50% equity is assumed. Additional capital investment assumptions may be found in the TVA five process cost study (9).

Annual revenue requirements are based on 7000 hours of operation per year. Removal and disposal of fly ash is considered a function of the power plant and is not included in the FGD process evaluation. Charges for raw materials, labor, and utilities are projected to 1978. Maintenance costs are estimated as a percentage of direct investment; the percentage is varied according to the complexity of the process operations and equipment selected.

Water treatment is given partial coverage in the economics of each process. No investment area is developed for the cleaning and recycle of a water purge stream. A nominal $1.20/kgal is included in the revenue requirements to acknowledge the future need for this treatment.

Projected 1978 costs for raw materials, labor, and utilities are listed in Table 19.

Economics for each process are evaluated on a regulated power industry basis. Depreciation, capital charges, and overheads are estimated on a basis similar to that presented in the TVA five process cost study (9), where a more thorough discussion of revenue requirements may be found.

Working capital is estimated as the equivalent cost for 3 weeks of raw materials, 7 weeks of direct operating costs, and 7 weeks of overheads. It is listed in the notes at the bottom of the revenue requirements page, but is not included in total capital investment.

Lifetime economics have been projected for this report using the declining-load factors described in Table 18. Year-by-year costs are calculated by computer using the same method as is used for calculating the year-one annual revenue requirements, with the exception that capital charges decline annually proportional to the amount depreciated. Unit costs of raw materials, utilities, labor, and analyses remain constant at 1978 dollars.

TABLE 19. PROJECTED 1978 UNIT COSTS FOR RAW MATERIALS, LABOR, AND UTILITIES

	$/unit
Raw materials	
Limestone	6.00/ton
Sulfuric acid	54.00/ton
Ferric sulfate	85.00/ton
Aluminum sulfate	150.00/ton
Manganese sulfate	0.065/lb
Labor	
Operating labor	10.00/man-hr
Analyses	15.00/man-hr
Utilities	
Steam	1.40/klb
Process water	0.11/kgal
Electricity	0.027/kWh
Water treatment	1.20/kgal

PROCESS DESCRIPTIONS

Simply stated, a limestone scrubbing system contacts flue gas with limestone slurry in an absorption chamber to remove SO_2. Cleaned gas flows to the stack and the calcium-sulfur compounds formed by the absorption of SO_2 by limestone are discarded in a disposal pond. To reclaim the sulfur in SO_2 in a potentially usable form, several systems have been designed which combine the flue gas SO_2 with calcium to form gypsum, $CaSO_4 \cdot 2H_2O$, a useful and environmentally more acceptable product than throwaway sludge. For gypsum production, such operations as oxidation, reaction with limestone outside the absorber, and separation of gypsum have been added to the scrubbing operation. These additional process steps can be carried out in several ways.

Three processes which produce gypsum have been selected for evaluation in this study. TVA engineers have developed a conceptual process design which combines the basic limestone scrubbing system with oxidation technology developed in Japan. Chiyoda's Thoroughbred 101 FGD system, developed and commercially available in Japan, combines absorption and oxidation in one vessel. The Dowa process, a commercial Japanese FGD system, is similar to U.S. double alkali processes except that it uses limestone to produce gypsum and scrubs with aluminum instead of sodium salts.

Complete process descriptions including flowsheet and material balance are reported for the limestone slurry, limestone-gypsum, Chiyoda, and Dowa processes. Brief summaries of process operation and simplified process diagrams are outlined for nine additional FGD gypsum-producing systems.

Limestone Slurry Process

The limestone slurry process for desulfurization of flue gas, Figures 7 and 8, is based on the process outlined in Detailed Cost Estimates For Advanced Effluent Desulfurization Processes (EPA-600/2-75-006; PB 242.541/1WP, January 1975) with modifications to use an ESP rather than a wet scrubber for upstream removal of fly ash. Simplified process chemistry includes the following reactions:

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$H_2SO_3 + CaCO_3 \rightarrow CaSO_3 \cdot 1/2H_2O + CO_2 + 1/2H_2O$$

The general process description is given below to simplify comparison of this process with the limestone-gypsum process which is discussed later.

Makeup limestone slurry from the feed preparation area is combined with scrubber effluent slurry and recycle pond water to control the concentration of the recirculating slurry at about 10% solids. This slurry is circulated through mobile-bed absorbers where it reacts with the SO_2 in the flue gas. The absorbers are equipped with chevron-type entrainment separators with provisions for upstream wash with fresh makeup water to control entrainment carryover in the gas stream. A bleedstream from the effluent hold tank is fed to the pond feed tank and the spent slurry is pumped to the onsite pond where the solids in the slurry settle to form a sludge containing about 40% solids. Pond supernate is recycled to the wet ball mills and the absorber effluent hold tank to maintain closed-loop operation. Scrubber outlet gas is reheated by indirect steam reheat and passed through the ID fans before entering the stack.

Minor adjustments were made to the reheater and gas-handling area design and costs from the initial study to reflect the changes associated with utilization of an ESP for particulate removal.

Limestone-Gypsum Process

The limestone-oxidation to gypsum process evaluated in this study, Figures 9 and 10, is a conceptual design to be used for comparison with other gypsum-processing processes. The process scrubbing area is similar in design to the scrubbing area for the limestone process. Downstream of the scrubbers, however, oxidation and filtration equipment (based on technology developed in Japan) have been added for conversion of the

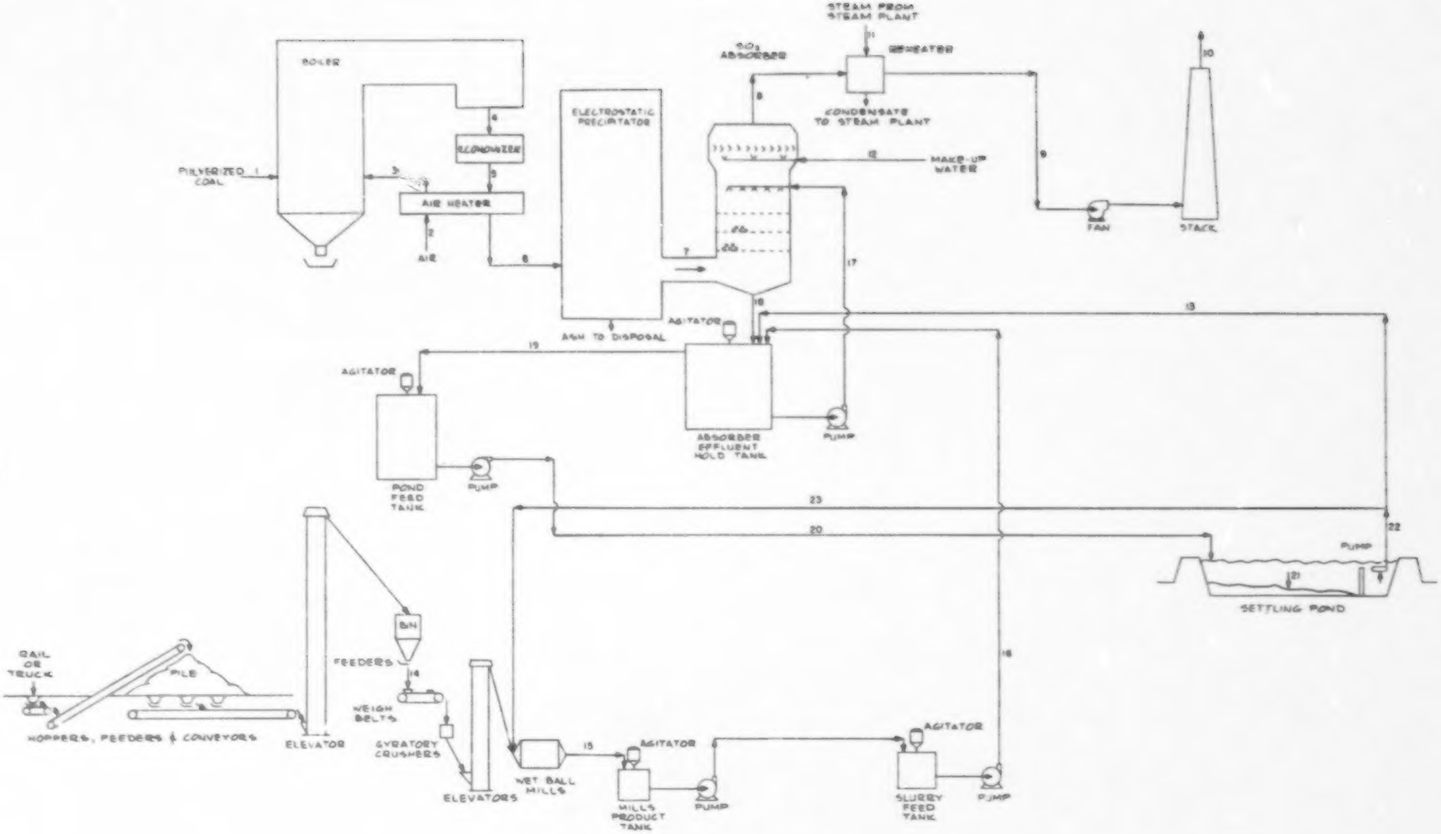
BOILER
PULVERIZED COAL
1
2
AIR
3
4
ECONOMIZER
5
AIR HEATER
6
ELECTROSTATIC PRECIPITATOR
ASH TO DISPOSAL
7
SO_2 ABSORBER
8
STEAM FROM STEAM PLANT
11
REHEATER
CONDENSATE TO STEAM PLANT
12
MAKE-UP WATER
9
FAN
STACK
10
17
18
AGITATOR
ABSORBER EFFLUENT HOLD TANK
PUMP
13
19
AGITATOR
POND FEED TANK
PUMP
23
20
22
PUMP
21
SETTLING POND
RAIL OR TRUCK
PILE
HOPPERS, FEEDERS & CONVEYORS
ELEVATOR
BIN
FEEDERS
14
WEIGH BELTS
GYRATORY CRUSHERS
ELEVATORS
WET BALL MILLS
15
AGITATOR
MILLS PRODUCT TANK
PUMP
AGITATOR
SLURRY FEED TANK
PUMP
16

Figure 7. Limestone slurry process. Flow diagram.

STREAM NO	1	2	3	4	5	6	7	8	9	10	11	12	13
DESCRIPTION	COAL TO BOILER	COMBUSTION AIR TO AIR HEATER	COMBUSTION AIR TO BOILER	GAS TO ECONOMIZER	GAS TO AIR HEATER	GAS TO ESP (99.5%)	GAS TO ABSORBER	GAS TO REHEATER	GAS TO FAN	GAS TO ATMOSPHERE	STEAM TO GAS REHEATER	MAKE-UP WATER TO SO_2 ABSORBER	POND WATER TO A. E. H. T.
RATE, LBS./HR.	375K	4,518K	4,075K	4404K	4,404K	1,212K	1,212K	1,262K	1,262K	5,048K	17.6K	81.4K	77.3K
SCFM		984K	888K	943K	943K	260K	260K	290K	290K	1,161K			
GPM												163	155
PARTICULATES, LBS./HR.				33.7K	33.7K	8,435	42.2	55.9	55.9	224			
TEMPERATURE, °F.		110	535	890	705	310	310	125	163	175	470		
SPECIFIC GRAVITY													
UNDISSOLVED SOLIDS, %													
NO. OF STREAMS	1	1	1	1	1	4	4	4	4	1	4	4	4

STREAM NO.	14	15	16	17	18	19	20	21	22	23
DESCRIPTION	LIMESTONE TO WEIGH FEEDER	SLURRY TO MILLS PRODUCT TANK	LIMESTONE SLURRY TO A.E.H.T.	RECYCLE SLURRY TO SO_2 ABSORBER	SO_2 ABSORBER SLURRY TO A.E.H.T.	A.E.H.T. OVERFLOW TO POND FEED TK.	USED SLURRY TO SETTLING POND	SETTLED USED SLURRY	RECYCLE POND WATER	POND WATER TO WET BALL MILL
RATE, LBS./HR.	25K	39.6K	19.8K	11.99M	12.07M	177K	708K	180K	500K	14.6K
SCFM										
GPM		48.0	24.0	22.8K	23K	319	1276	277	1000	29.2
PARTICULATES, LBS./HR										
TEMPERATURE, °F.										
SPECIFIC GRAVITY		1.65				1.11		1.3		
UNDISSOLVED SOLIDS, %		60				10		40		
NO. OF STREAMS	2	2	4	4	4	4	1	1	1	2

Figure 8. Limestone slurry process. Material balance.

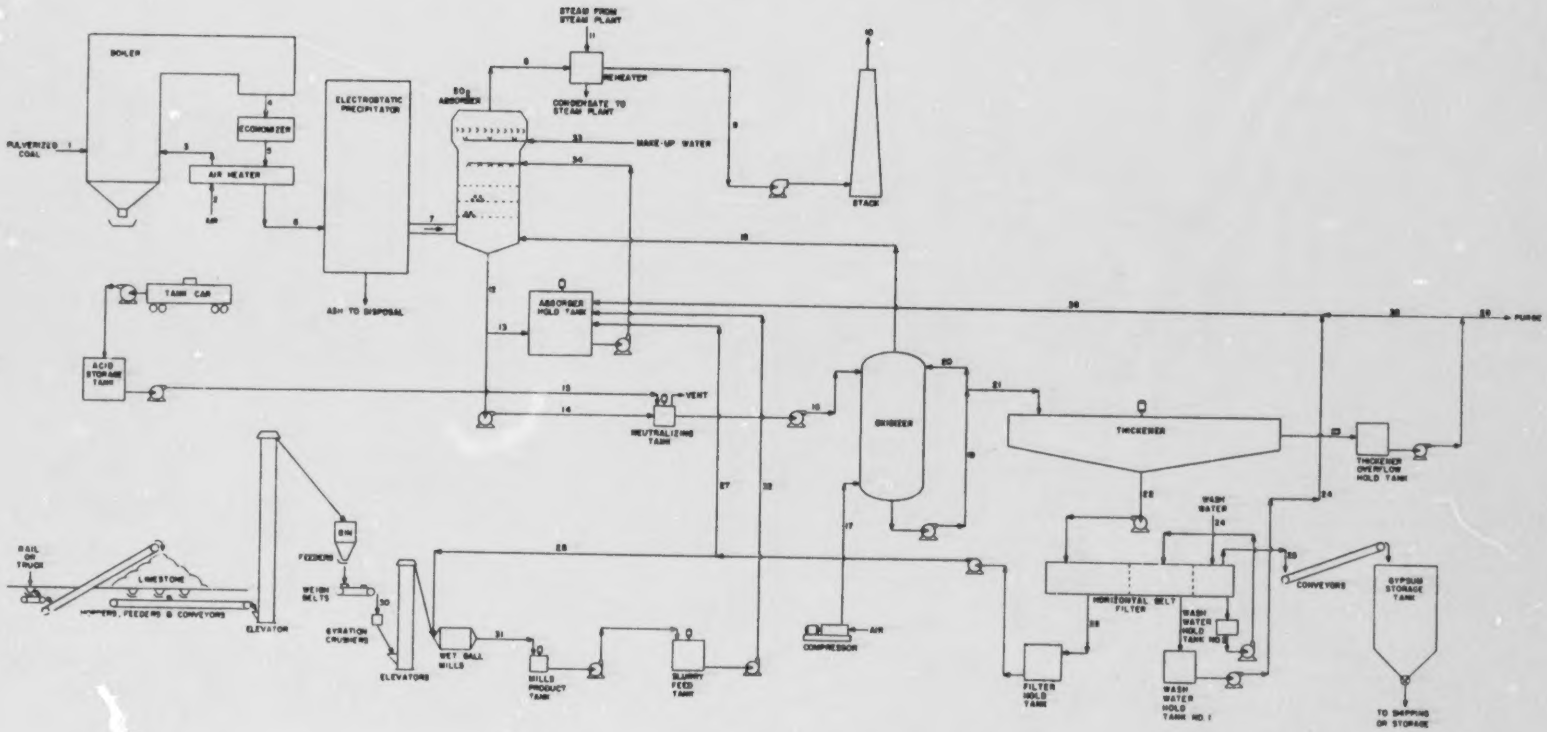
BOILER
PULVERIZED COAL
ECONOMIZER
AIR HEATER
AIR
ELECTROSTATIC PRECIPITATOR
ASH TO DISPOSAL
SO2 ABSORBER
STEAM FROM STEAM PLANT
REHEATER
CONDENSATE TO STEAM PLANT
MAKE-UP WATER
STACK
TANK CAR
ACID STORAGE TANK
ABSORBER HOLD TANK
VENT
NEUTRALIZING TANK
OXIDIZER
COMPRESSOR
AIR
THICKENER
THICKENER OVERFLOW HOLD TANK
PURGE
WASH WATER
HORIZONTAL BELT FILTER
WASH WATER HOLD TANK NO. 2
WASH WATER HOLD TANK NO. 1
FILTER HOLD TANK
CONVEYORS
GYPSUM STORAGE TANK
TO SHIPPING OR STORAGE
RAIL OR TRUCK
LIMESTONE
HOPPERS, FEEDERS & CONVEYORS
ELEVATOR
BIN
FEEDERS
WEIGH BELTS
GYRATION CRUSHERS
ELEVATORS
WET BALL MILLS
MILLS PRODUCT TANK
SLURRY FEED TANK

Figure 9. Limestone-gypsum process. Flow diagram.

STREAM NO	1	2	3	4	5	6	7	8	9	10	11	12	13
DESCRIPTION	COAL TO BOILER	COMBUSTION AIR TO AIR HEATER	COMBUSTION AIR TO BOILER	GAS TO ECONOMIZER	GAS TO AIR HEATER	GAS TO ESP (99.5%)	GAS TO ABSORBER	GAS TO REHEATER	GAS TO FAN	GAS TO ATMOSPHERE	STEAM	ABSORBER SLURRY EFFLUENT	ABSORBER SLURRY TO HOLD TANK
RATE LBS/HR	375K	4518K	4075K	4404K	4404K	1212K	1212K	1282K	1282K	5129K	188K	12094K	11998K
SCFM		984K	888K	943K	943K	260K	260K	295K	295K	1179K			
GPM												22K	21.8K
PARTICULATES LBS/HR				33.7K	33.7K	8435	42.2	55.9	55.9	224			
TEMPERATURE °F		110	535	890	705	310	310	125	165	175	470	125	125
SPECIFIC GRAVITY												1.1	1.1
UNDISSOLVED SOLIDS, %												15	15
NO OF STREAMS	1	1	1	1	1	4	4	4	4	1	4	4	4

STREAM NO	14	15	16	17	18	19	20	21	22	23	24	25
DESCRIPTION	ABSORBER BLEED TO NEUTRALIZER	H_2SO_4 TO NEUTRALIZER	NEUTRALIZED SOLUTION TO OXIDIZER	AIR TO OXIDIZER	OXIDIZER OFF GAS TO ABSORBER	OXIDIZER EFFLUENT SLURRY	RECYCLE SLURRY TO OXIDIZER	OXIDIZER BLEED TO THICKENER	THICKENER UNDERFLOW TO FILTER	THICKENER OVERFLOW	WASH WATER TO FILTER	FILTER CAKE TO BIN
RATE LBS/HR	98.3K	6.9K	400K	84.9K	20.3K	806.8K	403.4K	403.4K	98.7K	51.5K	30K	43.0K
SCFM				20K	4.8K							
GPM	179	7.5	714			1428	714	714	159	103	60	
PARTICULATES LBS/HR												
TEMPERATURE °F	125	77	125	60	125	125	125	125	60	60	60	60
SPECIFIC GRAVITY	1.1	1.831	1.12					1.13	1.25	1.0	1.0	
UNDISSOLVED SOLIDS, %	15		15					15	35	0	0	80
NO OF STREAMS	4	1	1	1	4	1	1	1	2	4	2	2

STREAM NO	26	27	28	29	30	31	32	33	34	35	36
DESCRIPTION	FILTRATE RETURN	FILTRATE TO ABSORBER HOLD TANK	FILTRATE TO BALL MILL	THICKENER OVERFLOW TO PURGE	LIMESTONE TO WEIGH FEEDER	SLURRY TO MILLS PRODUCT TANK	SLURRY TO ABSORBER HOLD TANK	MAKE-UP WATER	RECYCLE TO ABSORBER	OVERFLOW TO ABSORBER HOLD TANK	RECYCLE TO ABSORBER HOLD TANK
RATE LBS/HR	55.8K	20.6K	14.5K	22.1K	24.6K	39.0K	19.5K	63.7K	12030K	29.4K	44.4K
SCFM											
GPM	110	41.2	29	44.3		49	24.5	127.3	21.9K	58.8	88.8
PARTICULATES LBS/HR											
TEMPERATURE °F	60	60	60	60			60	60	125	60	60
SPECIFIC GRAVITY	1.0	1.0	1.0	1.0		1.61	1.61	1.0	1.1	1.0	1.0
UNDISSOLVED SOLIDS, %	0	0	0	0		60	60	0	15	.0	0
NO. OF STREAMS	2	4	2	4	2	2	4	4	4	4	4

Figure 10. Limestone-gypsum process. Material balance.

calcium sulfite in the slurry to gypsum. Simplified process chemistry includes the following reactions.

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$H_2SO_3 + CaCO_3 \rightarrow CaSO_3 \cdot 1/2H_2O + CO_2 + 1/2H_2O$$

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

$$CaSO_3 \cdot 1/2H_2O + 1/2O_2 + 3/2H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

A bleedstream from the scrubber effluent hold tank is fed to a neutralization reactor where it is contacted with 98% H_2SO_4 to (1) convert excess $CaCO_3$ in the slurry to $CaSO_4 \cdot 2H_2O$ and (2) lower the pH of the stream to approximately 4.0-4.5 to facilitate downstream oxidation. Sulfuric acid at an H_2SO_4:$CaCO_3$ stoichiometry of approximately 0.75 is added. The reaction byproduct is fed to a high-pressure oxidizer where the slurry is contacted with air to oxidize $CaSO_3 \cdot 1/2H_2O$ to $CaSO_4 \cdot 2H_2O$. Because of blinding of the limestone by $CaSO_4 \cdot 2H_2O$ formation on the exterior of the $CaCO_3$ particles and the low H_2SO_4:$CaCO_3$ stoichiometry used, tests have shown that the resulting slurry cake contains about 6% unreacted $CaCO_3$. Since wallboard- or cement-quality gypsum contains up to 15% $CaCO_3$, with the nominal grade containing between 8-15% $CaCO_3$, the product gypsum should be acceptable for wallboard. During the dewatering step the pH of the slurry gradually increases to about 6.0 due to buffering from the unreacted limestone.

Oxidation of $CaSO_3 \cdot 1/2H_2O$ to $CaSO_4 \cdot 2H_2O$ is affected by temperature, pressure, pH of the slurry, and the size of air bubbles. A stoichiometry of 3.0 mols O_2 per mol SO_3 is used for oxidation. A rotary diffuser breaks the air into small bubbles, thereby increasing the liquid-gas contact area. Oxidation occurs at a temperature of about 125°F and a pressure of 50-100 psig.

The effluent from the oxidizer is fed to a thickener to increase the concentration of solids in the slurry and facilitate dewatering. The thickener is smaller than that needed for a sulfite-sulfate sludge due to the excellent settling characteristics of the $CaSO_4 \cdot 2H_2O$. Since the retention time of the slurry in the thickener is about 44 hours, the unreacted limestone in the slurry acts as a buffer and the pH of the liquor increases to about 6-7. The filtration equipment can then be constructed of common materials. Also, the pH of the waste stream is more acceptable.

A purge stream is removed from the thickener overflow tank for treatment to remove soluble chloride ions and other trace elements to prevent a buildup of these process contaminants in the processing streams. A reverse osmosis water treatment process is used.

The gypsum is separated from the thickener underflow using a horizontal belt filter. This filter is capable of producing a gypsum cake containing over 80% dry solids and is designed with a wash section. The cake is composed of 94% $CaSO_4 \cdot 2H_2O$ and 6% $CaCO_3$ on a dry basis. The American Society for Testing and Materials has imposed limitations on the quality of soluble impurities in the dry gypsum of 0.05% by weight. The wash section of the filter is capable of reducing the quantity of soluble impurities to this level. In closed-loop operation the thickener overflow and filter hold tank water is recycled back to the absorber hold tank and the wet ball mill.

Chiyoda Thoroughbred 101 FGD Process

The Chiyoda process, Figures 11 and 12, uses dilute (2-3%) sulfuric acid as the SO_2 scrubbing liquor. A bleedstream from the absorber is neutralized with limestone slurry and gypsum is precipitated. Simplified process chemistry includes the following reactions.

Absorption: $SO_2 + H_2O \rightarrow H_2SO_3$

Oxidation: $H_2SO_3 + 1/2O_2 \rightarrow H_2SO_4$

Neutralization: $H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$

Flue gas flows from the air heater to an ESP where an assumed 99.5% of the fly ash is removed. The gas then enters the absorber near the bottom and flows upward through the outer chamber of the vessel. Cleaned gas leaves the absorber through a mist eliminator and passes through a reheater before leaving the stack.

The Chiyoda absorber is designed with a center column which functions as the oxidation tower. Liquor containing the absorbed SO_2 as sulfurous acid, H_2SO_3, is pumped from the bottom of the outer chamber into the bottom of the oxidation chamber and flows upward cocurrently with the injected air. In the presence of the ferric sulfate catalyst, H_2SO_3 is completely oxidized to sulfuric acid. The rich liquor overflows the top of the oxidizer column and returns to the bottom of the vessel through the outer chamber.

A bleedstream of rich liquor is reacted with limestone in a Chiyoda-designed crystallizer to form gypsum crystals. Only partial neutralization is allowed; complete neutralization results in precipitation of the ferric ion as ferric hydroxide. Gypsum formed in the crystallizer is separated by a rotary drum filter and a product of 80% solids is conveyed to the storage-shipping area. Liquor from the crystallizer and the filter is clarified in a thickener and returned to the absorber. Thickener underflow is recycled to the crystallizer. A wastewater purge is included in the process to control chlorine buildup and protect the absorber from corrosion.

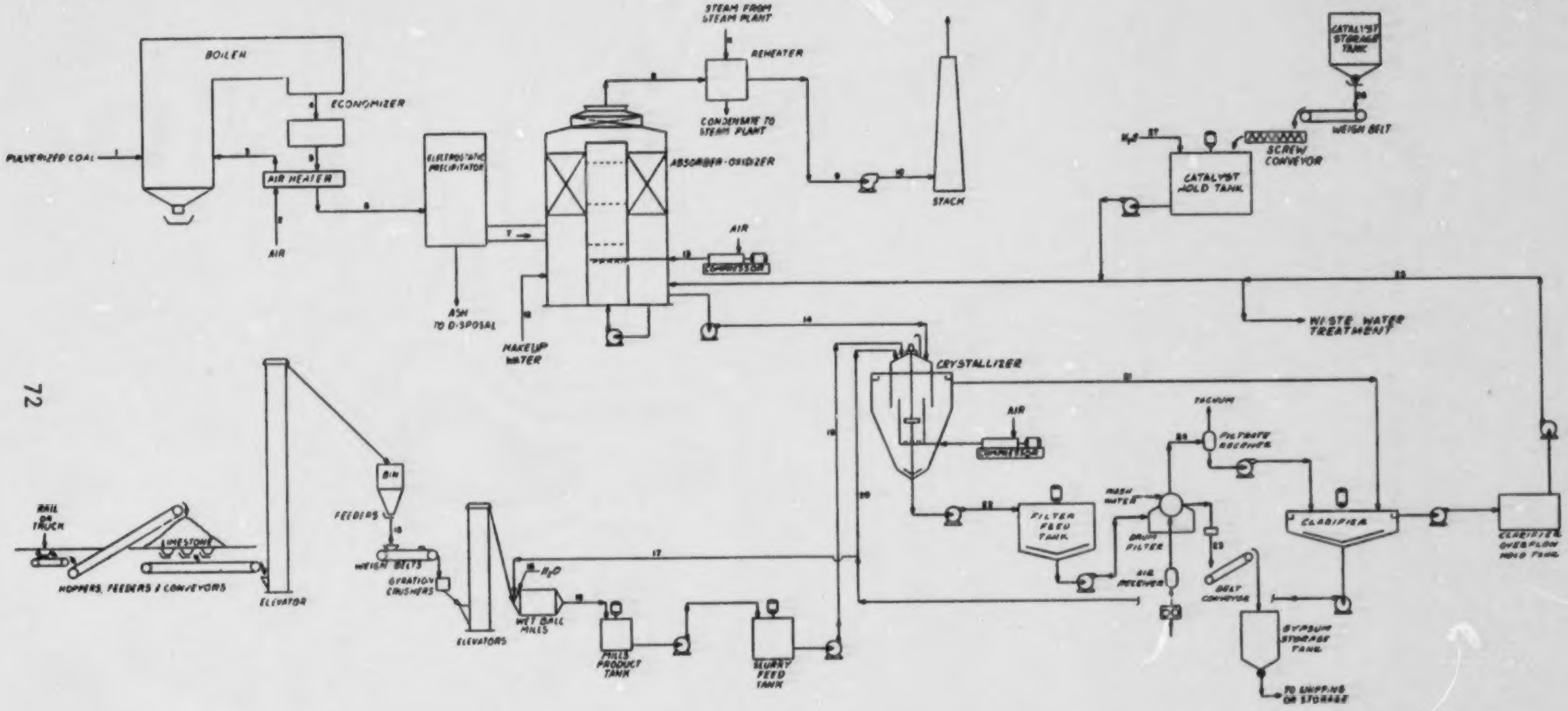
BOILER
ECONOMIZER
PULVERIZED COAL
AIR HEATER
AIR
ELECTROSTATIC PRECIPITATOR
ASH TO DISPOSAL
STEAM FROM STEAM PLANT
REHEATER
CONDENSATE TO STEAM PLANT
ABSORBER-OXIDIZER
AIR
COMPRESSOR
MAKEUP WATER
STACK
CATALYST STORAGE TANK
WEIGH BELT
SCREW CONVEYOR
H_2O
CATALYST HOLD TANK
WASTE WATER TREATMENT
CRYSTALLIZER
AIR
COMPRESSOR
VACUUM
FILTRATE RECEIVER
WASH WATER
FILTER FEED TANK
DRUM FILTER
AIR RECEIVER
BELT CONVEYOR
CLARIFIER
CLARIFIER OVERFLOW HOLD TANK
GYPSUM STORAGE TANK
TO SHIPPING OR STORAGE
RAIL OR TRUCK
LIMESTONE
HOPPERS, FEEDERS & CONVEYORS
ELEVATOR
BIN
FEEDERS
WEIGH BELTS
GYRATION CRUSHERS
ELEVATORS
H_2O
WET BALL MILLS
MILLS PRODUCT TANK
SLURRY FEED TANK

Figure 11. Chiyoda Thoroughbred 101 FGD process. Flow diagram.

STREAM NO	1	2	3	4	5	6	7	8	9	10	11	12	13
DESCRIPTION	COAL TO BOILER	COMBUSTION AIR TO AIR HEATER	COMBUSTION AIR TO BOILER	GAS TO ECONOMIZER	GAS TO AIR HEATER	GAS TO ELECTROSTATIC PRECIPITATOR	GAS TO ABSORBER	GAS TO REHEATER	GAS TO FAN	GAS TO STACK	STEAM TO GAS REHEATER	MAKEUP WATER TO ABSORBER	AIR TO OXIDIZER
RATE, LBS/HR	375K	4,518K	4,075K	4,404K	4,404K	1,212K	1,212K	1,275.5K	1,275.5K	5,102K	18.2K	54,830	16,730
SCFM (60°F)		984K	888K	943K	943K	260K	260K	281K	281K	281K			3,685
GPM												110	
PARTICULATES, LBS/HR				33.7K	33.7K	8,435	42.2	42.2	42.2	168.8			
TEMPERATURE, °F		110	535	890	705	310	310	125	164	175	470		
SPECIFIC GRAVITY													
UNDISSOLVED SOLIDS, %													
NO OF STREAMS	1	1	1	1	1	4	4	4	4	1	4	4	4

STREAM NO	14	15	16	17	18	19	20	21	22	23	24	25
DESCRIPTION	SULFURIC ACID BLEED TO CRYSTALLIZER	LIMESTONE TO WEIGH FEEDER	MAKEUP WATER TO BALL MILL	CLARIFIER UNDERFLOW TO BALL MILL	SLURRY TO MILLS PRODUCT TANK	LIMESTONE SLURRY TO CRYSTALLIZER	CLARIFIER UNDERFLOW TO CRYSTALLIZER	CRYSTALLIZER OVERFLOW TO CLARIFIER	UNDERFLOW TO FILTER FEED TANK	GYPSUM CAKE TO STORAGE/SHIP	FILTRATE TO CLARIFIER	SCRUBBING LIQUOR TO ABSORBER
RATE, LBS/HR	577,850	17,800	2,000	9,900	59,400	14,850	12,500	1,097,000	56,700	35,500	77,900	570,000
SCFM (60°F)												
GPM	1,143		4	20	74	18	25	2,170	99		154	1,139
PARTICULATES, LBS/HR												
TEMPERATURE, °F												
SPECIFIC GRAVITY	1.01			1.01	1.61	1.61	1.01	1.01	1.15		1.01	1.0
UNDISSOLVED SOLIDS, %					60	60			25	80		
NO OF STREAMS	4	2	2	2	1	4	4	2	4	2	2	4

STREAM NO	26	27									
DESCRIPTION	CATALYST MAKEUP	WATER TO CATALYST TANK									
RATE, LBS/HR											
SCFM	145	210									
GPM		0.4									
PARTICULATES LBS/HR											
TEMPERATURE, °F											
SPECIFIC GRAVITY											
UNDISSOLVED SOLIDS, %											
NO OF STREAMS	1	1									

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Figure 12. Chiyoda Thoroughbred 101 FGD process. Material balance.

The flowsheet and the detailed engineering for this evaluation were done by TVA in compliance with the premises outlined in this report for the purpose of comparison with the other selected processes. System capital and operating costs are dependent on the design premises made by TVA; however, these premises do not necessarily match those made by Chiyoda in optimizing flow rates and design conditions for a specific application. As an example, Chiyoda would design a 500-MW unit with two rather than four scrubbing trains, would use a prescrubber, and would not use indirect steam reheat. Certain process information is considered by Chiyoda to be proprietary and has been deleted from the report.

The Chiyoda Thoroughbred 101 process (CT-101) was developed by Chiyoda Chemical Engineering and Construction Company, Ltd., Yokohama, Japan. Currently, there are 15 commercial installations in Japan, treating gas from oil-fired utility boilers, Claus sulfur plants, and industrial waste incinerators. A 23-MW-equivalent-capacity demonstration unit operates at Scholz Steam Plant, Sneads, Florida, a utility of Gulf Power Company. The process is available in the United States through Chiyoda International Corporation, Seattle, Washington.

Chiyoda began lab tests for an advanced FGD system in October 1975. Named Chiyoda Thoroughbred 121 (CT-121), the process combines absorption, oxidation, and crystallization into one reactor vessel. There is no process chemistry change involved.

The integrated vessel design replaces the CT-101 absorber-oxidizer with a flue gas bubbling contact zone which is placed on top of the CT-101 crystallizer. Claims made by Chiyoda for their new system include lower investment cost and less energy required for operation.

Dowa Aluminum Sulfate-Gypsum Process

Double-alkali systems use a soluble reactant to absorb SO_2 from flue gas and a second alkali (lime or limestone) to precipitate the absorbed SO_2. Introduction of lime or limestone outside the absorption chamber reduces the scaling that is a problem in direct lime-limestone slurry scrubbing.

The Dowa process, Figures 13 and 14, is a double-alkali scrubbing system that uses aluminum sulfate solution to absorb the SO_2 and limestone slurry to precipitate gypsum and regenerate the aluminum sulfate liquor. Simplified process chemistry includes the following reactions.

Absorption: $Al_2(SO_4)_3 \cdot Al_2O_3 + 3SO_2 \rightarrow Al_2(SO_4)_3 \cdot Al_2(SO_3)_3$

Oxidation: $Al_2(SO_4)_3 \cdot Al_2(SO_3)_3 + 3/2O_2 \rightarrow 2Al_2(SO_4)_3$

Neutralization: $2Al_2(SO_4)_3 + 3CaCO_3 + 6H_2O \rightarrow Al_2(SO_4)_3 \cdot Al_2O_3 +$ $3CaSO_4 \cdot 2H_2O$ (gypsum) $+ 3CO_2$

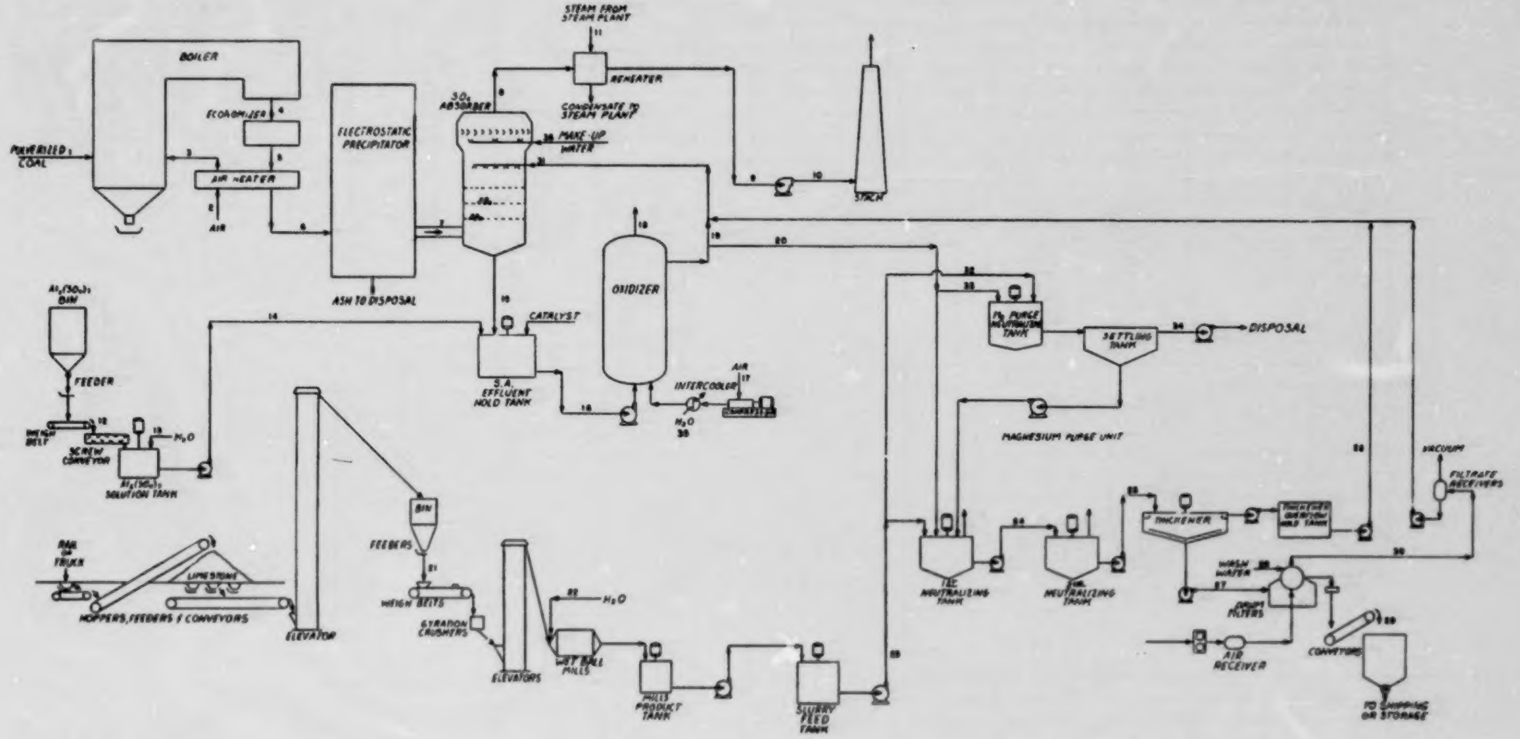
PULVERIZED COAL
BOILER
ECONOMIZER
AIR HEATER
AIR
ELECTROSTATIC PRECIPITATOR
ASH TO DISPOSAL
SO_2 ABSORBER
MAKE-UP WATER
STEAM FROM STEAM PLANT
REHEATER
CONDENSATE TO STEAM PLANT
STACK
OXIDIZER
CATALYST
S.A. EFFLUENT HOLD TANK
AIR
INTERCOOLER
H_2O
$Al_2(SO_4)_3$ BIN
FEEDER
WEIGH BELT
SCREW CONVEYOR
H_2O
$Al_2(SO_4)_3$ SOLUTION TANK
RAIL OR TRUCK
LIMESTONE
HOPPERS, FEEDERS & CONVEYORS
ELEVATOR
BIN
FEEDERS
WEIGH BELTS
GYRATION CRUSHERS
ELEVATORS
H_2O
WET BALL MILLS
MILLS PRODUCT TANK
SLURRY FEED TANK
Mg PURGE NEUTRALIZING TANK
SETTLING TANK
DISPOSAL
MAGNESIUM PURGE UNIT
1st NEUTRALIZING TANK
2nd NEUTRALIZING TANK
THICKENER
THICKENER OVERFLOW HOLD TANK
WASH WATER
DRUM FILTERS
AIR RECEIVER
CONVEYORS
TO SHIPPING OR STORAGE
VACUUM
FILTRATE RECEIVERS

Figure 13. Dowa aluminum sulfate-gypsum process. Flow diagram.

STREAM NO.	1	2	3	4	5	6	7	8	9	10	11	12	13
DESCRIPTION	COAL TO BOILER	COMBUSTION AIR TO AIR HEATER	COMBUSTION AIR TO BOILER	GAS TO ECONOMIZER	GAS TO AIR HEATER	GAS TO ELECTROSTATIC PRECIPITATOR	GAS TO ABSORBER	GAS TO REHEATER	GAS TO FAN	GAS TO STACK	STEAM TO GAS REHEATER	ALUMINUM SULFATE (50%) TO SOLN. TANK	MAKEUP H_2O TO $Al_2(SO_4)_3$ SOLN. TANK
RATE, LBS/HR	375K	4,518K	4,075K	4,404K	4,404K	1,212K	1,212K	1,275.5K	1,275.5K	5,102K	18.2K	560	600
SCFM (60°F)		984K	888K	943K	943K	260K	260K	281K	281K	281K			
GPM													1.2
PARTICULATES, LBS/HR.				33.7K	33.7K	8,435	42.2	42.2	42.2	1688			
TEMPERATURE, °F		110	535	890	705	310	310	125	164	175	470		
SPECIFIC GRAVITY													
UNDISSOLVED SOLIDS, %													
NO OF STREAMS	1	1	1	1	1	4	4	4	4	1	4	1	1

STREAM NO	14	15	16	17	18	19	20	21	22	23	24	25
DESCRIPTION	$Al_2(SO_4)_3$ SOLUTION TO HOLD TANK	ABSORBER SOLUTION TO HOLD TANK	SOLUTION TO OXIDATION	AIR TO COMPRESSOR	VENT FROM OXIDATION	SOLUTION TO ABSORBER	SOLUTION TO FIRST NEUT. TANK	LIMESTONE TO WEIGH FEEDER	MAKEUP WATER TO BALL MILL	LIMESTONE SLURRY TO NEUT. TANK	GYPSUM SLURRY TO SECOND NEUT. TANK	GYPSUM SLURRY TO THICKENER
RATE, LBS/HR	1,100	0	0	8,375	7,380	0	0	35,600	20,800	56,400	0	0
SCFM (60°F)				1,840	1,620							
GPM	1.7	0	0			0	0		42	70	0	0
PARTICULATES, LBS/HR.												
TEMPERATURE, °F												
SPECIFIC GRAVITY	1.29	1.2	1.2							1.61	1.23	1.24
UNDISSOLVED SOLIDS, %										60		
NO OF STREAMS	1	4	4	4	4	4	1	1	1	1	1	1

STREAM NO.		26	27	28	29	30	31	32	33	34	35	36
DESCRIPTION		OVERFLOW FROM HOLD TANK	UNDERFLOW TO FILTER	WASH WATER TO FILTER	GYPSUM CAKE TO SHIPPING/STGE	FILTRATE FROM FILTER	SCRUBBING LIQUOR TO ABSORBER	LIMESTONE SLURRY TO Mg PURGE	BLEED STREAM TO Mg PURGE TANK	PURGE STREAM TO DISPOSAL	WATER TO INTERCOOLER	MAKEUP H_2O TO ABSORBER
RATE, LBS/HR.		0	190,000	18,000	71,200	0	0	0	0	0	20,900	64,500
SCFM (60°F)												
GPM		0	270	21		0	0	0	0	0	42	122
PARTICULATES LBS/HR.												
TEMPERATURE, °F												
SPECIFIC GRAVITY		1.21				1.2	1.2	1.61				
UNDISSOLVED SOLIDS, %			30		80			60				
NO. OF STREAMS		1	1	2	1	2	4	1	1	1	4	4

Figure 14. Dowa aluminum sulfate-gypsum process. Material balance.

Flue gas is taken from the air preheater to an ESP where 99.5% of the fly ash is removed. The gas then enters the absorber near the bottom and flows upward through the tower. The aluminum sulfate solution flows countercurrently to the gas and the aluminum sulfate reacts with the SO_2 to form an aluminum sulfate-sulfite compound. The scrubbed gas leaves through a mist eliminator and passes through a reheater before leaving the stack.

The SO_2-rich absorber solution flows to a hold tank from which it is pumped to an oxidizer. Excess air is sparged through specially designed nozzles in the oxidizer to convert sulfite to sulfate. Most of the oxidized solution is recycled to the absorber.

A bleedstream from the oxidizer is fed to the first of two neutralizing tanks in series where limestone as a 15% slurry is introduced to react with aluminum sulfate. Gypsum is produced in these tanks and the aluminum sulfate-oxide solution is regenerated for recycle to the absorber.

The gypsum slurry is pumped to a thickener where it settles to a concentration of 30% solids. The thickener underflow is dewatered in a rotary drum filter to produce a gypsum cake of 80% solids which can be either stockpiled or shipped directly. Filtrate, cake wash water, and thickener overflow are returned to the absorber.

Both magnesium and chloride buildup in the liquor must be avoided for successful operation of the process. Magnesium contamination from the limestone, while not affecting SO_2 absorption, reduces the quality of the gypsum produced. Chlorides enters the system from coal and from makeup water and is a potential problem that can range from corrosion of the FGD process equipment to weakening of the finished wallboard.

To solve the problem of these impurities, Dowa has built a purge or de-magnesium unit into its process. About 2% of the bleedstream to the neutralizer is diverted to a purge tank. Limestone is added and gypsum and aluminum hydroxide are precipitated. Magnesium remains in solution and is pumped from the tank overflow to the wastewater treatment area. Underflow from the tank is pumped to the main neutralizing tank where the aluminum hydroxide dissolves and is reused as scrubbing liquor.

The flowsheet and the detailed engineering for this evaluation were done by TVA in compliance with the premises outlined in this report for the purpose of comparison with the other selected processes. System capital and operating costs are dependent on the design premises made by TVA; however, these premises do not necessarily match those made by Dowa in optimizing flow rates and design conditions for a specific application. Certain process information is considered by Dowa to be proprietary and has been deleted from the report.

The Dowa aluminum sulfate process was developed by the Dowa Mining Company, Ltd., Tokyo, Japan. The process is commercially operational at five Japanese locations treating gas from a molybdenum sulfide roaster, a sulfuric acid plant, an antimony sulfide converter, an oil-burning boiler, and an iron ore sintering plant. Universal Oil Products, Inc., (UOP) Des Plaines, Illinois, is presently negotiating a licensing agreement with Dowa to manufacture and sell the Dowa system in the United States.

Other Gypsum-Producing Processes

Nine additional alternative gypsum-producing processes are discussed in Appendix A to give a more complete understanding of the variety of systems available for recovering SO_2 as marketable gypsum.

ECONOMIC EVALUATION AND COMPARISON

Using the premises outlined previously for base case conditions, investment and revenue requirements have been estimated for limestone slurry, limestone-gypsum, Chiyoda, and Dowa. Several methods for displaying cost results are included.

Capital Investment

Investment estimates include an itemized equipment list, area breakdown, and investment summary for each process. Itemized equipment lists, divided into process areas, are presented in Appendix B, Tables B-1 through B-4. Costs are estimated in 1977 dollars and are derived from vendor contacts, actual TVA purchase costs for similar process equipment, and authoritative publications of estimating standards. These equipment lists are useful for providing equipment cost breakdowns for the investment summaries and may also be used for comparing alternative process equipment specifications from process to process. As an illustration, absorber descriptions including materials of construction from the four equipment lists are tabulated below.

Process	Item	No.	Description
Limestone slurry	Turbulent contact absorber (TCA)	4	SO_2 absorber, mobile bed, with demister, 41 ft long x 13 ft wide x 41 ft high; 1/4-inch carbon steel with neoprene lining; 316SS grids, high-density polyethylene spheres, FRP spray headers, chevron-vane mist eliminators
Limestone-gypsum	TCA	4	Same as limestone
Chiyoda	Chiyoda absorber-oxidizer	4	SO_2 absorber-oxidizer, 45 ft diameter outer chamber x 15 ft diameter inner chamber x 85 ft high, vertical double shell, 316L SS; polypropylene grid, 3-1/2 inch Tellerette packing, polypropylene mist eliminator
Dowa	TCA	4	Proprietary

Area-by-area summaries showing equipment and installation costs for each process are displayed in Appendix B, Tables B-5 through B-8. Installation expense includes a labor charge for installing each equipment unit plus installation costs for piping, ductwork, concrete, excavation and site preparation, structures, electrical equipment, instrumentation, buildings, and painting. Also included are land, utilities, services, and construction facilities.

For the limestone slurry and limestone-gypsum processes, installation expenses are determined individually based on detailed layout drawings and projected erection labor requirements. For the Chiyoda and Dowa processes, installation expenses are determined as a percentage of equipment cost based on projected erection labor requirements from TVA construction experience and from the literature. Although equipment costs are higher for the gypsum processes, the total investment is lower for two of the three processes assuming that the abatement gypsum is marketable and disposal ponds are not required. Storage of gypsum over the life of a 500-MW power unit burning 3.5% sulfur coal would require up to 100 additional acres, presenting a similar problem to that of disposing of waste solids in limestone-lime scrubbing.

Total investment requirements are summarized for each process in Tables 20-23 and a comparison of total investment in dollars and unit investment in dollars per kilowatt for the four processes is given in Table 24. Total capital investment ranges from \$24,394k (\$49/kW) to \$40,531k (\$81/kW).

The effect of power unit size on total capital investment is shown in Figure 15 for the limestone slurry and limestone-gypsum processes. A 200-MW power unit scrubbing with limestone slurry requires investment of \$14,400k , while a 1000-MW power unit requires \$44M investment for the same scrubbing process. The sensitivity of the limestone-gypsum process to variations in power unit size and sulfur content of coal is shown in Figure 16. Sulfur contents displayed are 2, 3.5, and 5% and result in investment requirements at 500-MW of \$22,600k, \$25,600k, and \$28,100k respectively. The relationship for limestone slurry is similar.

Revenue Requirements

Revenue requirements are displayed as first-year summaries for each of the four processes and lifetime revenue requirements for the limestone slurry and limestone-gypsum processes. The annual summaries, based on 7000 hours of operation, are displayed in Tables 25-28. In Table 29 a comparison is made of total dollars of annual revenue requirements and unit revenue requirements expressed in mills/kWh, ¢/MBtu heat input, and \$/ton coal burned, per ton sulfur removed, and per ton gypsum produced. The first-year annual revenue requirements excluding credit from sale of byproduct gypsum range from \$10,105,300 to \$15,483,400/year (2.89 mills/kWh to 4.42 mills/kWh).

TABLE 20. LIMESTONE SLURRY PROCESS

SUMMARY OF ESTIMATED FIXED INVESTMENT[a]

(500-MW new coal-fired power unit, 3.5% sulfur in fuel,
90% SO_2 removal, onsite solids disposal, 1977 cost basis)

	Investment, $	% of subtotal direct investment
Limestone receiving and storage (hoppers, feeders, conveyors, elevator, bins, dust collecting and bag filter systems)	571,000	3.1
Feed preparation (feeders, crushers, elevators, ball mills, tanks, agitators, pumps, dust collecting system, and hoist)	1,234,000	6.8
SO_2 scrubbers and ducts (4 TCA scrubbers including mist eliminators, effluent hold tanks, agitators, pumps, common feed plenum, and exhaust gas ducts to inlet of fan)	6,216,000	34.0
Stack gas reheat (4 indirect steam reheaters and soot blowers)	797,000	4.4
Gas handling (4 fans including exhaust gas ducts and dampers between fan and stack gas plenum)	1,977,000	10.8
Calcium solids disposal (onsite disposal facilities including feed tank, agitator, slurry disposal pumps, pond, liner, and pond water return pumps)	5,136,000	28.1
Land (140 acres)	490,000	2.7
Utilities (instrument air generation and supply system, plus distribution systems for obtaining process steam, water, and electricity from the power plant)	93,000	0.5
Service facilities (buildings, shops, stores, site development, roads, railroads, and walkways)	877,000	4.8
Construction facilities	870,000	4.8
Subtotal direct investment	18,261,000	100.0
Engineering design and supervision	1,643,000	9.0
Construction field expense	2,009,000	11.0
Contractor fees	913,000	5.0
Contingency	1,826,000	10.0
Subtotal fixed investment	24,652,000	135.0
Allowance for startup and modifications	1,972,000	10.8
Interest during construction (8%/annum rate)	1,972,000	10.8
Total capital investment	28,596,000	156.6

a. Basis
Stack gas reheat to 175°F by indirect steam reheat.
Disposal pond located 1 mile from power plant.
Midwest plant location represents project beginning mid-1975, ending mid-1978.
Average cost basis for scaling, mid-1977.
Minimum in-process storage; only pumps are spared.
Investment requirements for removal and disposal of fly ash excluded.
Construction labor shortages with accompanying overtime pay incentive not considered.

TABLE 21. LIMESTONE-GYPSUM PROCESS

SUMMARY OF ESTIMATED FIXED INVESTMENT[a]

(500-MW new coal-fired power unit, 3.5% sulfur in fuel, 90% SO_2 removal, 1977 cost basis)

	Investment, $	% of subtotal direct investment
Material handling (hoppers, feeders, conveyors, elevator, bins, dust collecting and bag filter systems)	571,000	3.5
Feed preparation (feeders, crushers, elevators, ball mills, tanks, agitators, pumps, dust collecting system, and hoist)	1,346,000	8.2
SO_2 scrubbers and ducts (4 TCA scrubbers including mist eliminators, effluent hold tanks, agitators, pumps, common feed plenum, and exhaust gas ducts to inlet of fan)	6,250,000	38.1
Stack gas reheat (4 indirect steam reheaters and soot blowers)	828,000	5.0
Gas handling (4 fans including exhaust gas ducts and dampers between fan and stack gas plenum)	1,977,000	12.1
Oxidation (high pressure oxidation tower, tanks, agitators, pumps, and air compressors)	1,258,000	7.7
Slurry processing (thickener, filters, tanks, and pumps)	2,145,000	13.1
Storage (conveyors and storage silo)	203,000	1.2
Land (18 acres)	63,000	0.4
Utilities (instrument air generation and supply system, plus distribution systems for obtaining process steam, water, and electricity from the power plant)	93,000	0.6
Service facilities (buildings, shops, stores, site development, roads, railroads, and walkways)	877,000	5.3
Construction facilities	781,000	4.8
Subtotal direct investment	16,392,000	100.0
Engineering design and supervision	1,475,000	9.0
Construction field expense	1,803,000	11.0
Contractor fees	820,000	5.0
Contingency	1,639,000	10.0
Subtotal fixed investment	22,129,000	135.0
Allowance for startup and modifications	1,770,000	10.8
Interest during construction (8%/annum rate)	1,770,000	10.8
Total capital investment	25,669,000	156.6

---

a. Basis

Stack gas reheat to 175°F by indirect steam reheat.

Midwest plant location represents project beginning mid-1975, ending mid-1978.

Average cost basis for scaling, mid-1977.

Minimum in-process storage; only pumps are spared.

Investment requirements for removal and disposal of fly ash excluded.

Construction labor shortages with accompanying overtime pay incentive not considered.

TABLE 22. CHIYODA THOROUGHBRED 101 FGD PROCESS

SUMMARY OF ESTIMATED FIXED INVESTMENT[a]

(500-MW new coal-fired power unit, 3.5% sulfur in fuel, 90% SO_2 removal, 1977 cost basis)

	Investment, $	% of subtotal direct investment
Material handling (hoppers, feeders, conveyors, elevator, bins, dust collecting and bag filter systems)	640,000	2.5
Feed preparation (feeders, crushers, elevators, ball mills, conveyor, tanks, agitators, pumps, dust collecting system, and hoist)	1,401,000	5.4
SO_2 absorption-oxidation (4 Chiyoda absorber-oxidation vessels, compressors, pumps, common feed plenum, and exhaust gas ducts to inlet of fan)	13,930,000	53.8
Reheat (4 indirect steam reheaters and soot blowers)	819,000	3.2
Gas handling (4 fans including exhaust gas ducts and dampers between fan and stack gas plenum)	2,071,000	8.0
Slurry processing (4 Chiyoda neutralizers, compressor, tanks, agitators, pumps, cyclones, centrifuges, and thickener)	4,237,000	16.4
Solids disposal (conveyor and storage silo)	203,000	0.8
Land (18 acres)	63,000	0.2
Utilities (instrument air generation and supply system, plus distribution systems for obtaining process steam, water, and electricity from the power plant)	117,000	0.4
Service facilities (buildings, shops, stores, site development, roads, railroads, and walkways)	1,168,000	4.5
Construction facilities	1,234,000	4.8
Subtotal direct investment	25,883,000	100.0
Engineering design and supervision	2,329,000	9.0
Construction field expense	2,847,000	11.0
Contractor fees	1,294,000	5.0
Contingency	2,588,000	10.0
Subtotal fixed investment	34,941,000	135.0
Allowance for startup and modification	2,795,000	10.8
Interest during construction (8%/annum rate)	2,795,000	10.8
Total capital investment	40,531,000	156.6

---

a. Basis

Stack gas reheat to 175°F by indirect steam reheat.

Midwest plant location represents project beginning mid-1975, ending mid-1978.

Average cost basis for scaling, mid-1977.

Minimum in-process storage; only pumps are spared.

Investment requirements for removal and disposal of fly ash excluded.

Construction labor shortages with accompanying overtime pay incentive not considered.

TABLE 23. DOWA BASIC ALUMINUM SULFATE-GYPSUM PROCESS

SUMMARY OF ESTIMATED FIXED INVESTMENT[a]

(500-MW new coal-fired power unit, 3.5% sulfur in fuel, 90% SO_2 removal, 1977 cost basis)

	Investment, $	% of subtotal direct investment
Material handling (hoppers, feeders, conveyors, elevator, bins, dust collecting and bag filter systems)	659,000	4.2
Feed preparation (feeders, crushers, elevators, ball mills, conveyor, tanks, agitators, pumps, dust collecting system, and hoist)	1,402,000	9.0
SO_2 absorption (4 TCA absorbers including mist eliminators, tanks, agitators, pumps, common feed plenum, and exhaust gas ducts to inlet of fan)	5,740,000	36.9
Reheat (4 indirect steam reheaters and soot blowers)	819,000	5.3
Gas handling (4 fans including exhaust gas ducts and dampers between fan and stack gas plenum)	2,071,000	13.3
Oxidation (towers and compressors)	852,000	5.5
Slurry processing (tanks, agitators, pumps, thickener, drum filters, and conveyor)	2,095,000	13.4
Purge unit (tanks, agitators, pumps)	158,000	1.0
Solids disposal (conveyor and storage silo)	203,000	1.3
Land (18 acres)	63,000	0.4
Utilities (instrument air generation and supply system, plus distribution systems for obtaining process steam, water, and electricity from the power plant)	70,000	0.4
Service facilities (buildings, shops, stores, site development, roads, railroads, and walkways)	703,000	4.5
Construction facilities	742,000	4.8
Subtotal direct investment	15,577,000	100.0
Engineering design and supervision	1,402,000	9.0
Construction field expense	1,714,000	11.0
Contractor fees	779,000	5.0
Contingency	1,558,000	10.0
Subtotal fixed investment	21,030,000	135.0
Allowance for startup and modification	1,682,000	10.8
Interest during construction (8%/annum rate)	1,682,000	10.8
Total capital investment	24,394,000	156.6

a. Basis

Stack gas reheat to 175°F by indirect steam reheat.

Midwest plant location represents project beginning mid-1975, ending mid-1978.

Average cost basis for scaling, mid-1977.

Minimum in-process storage; only pumps are spared.

Investment requirements for removal and disposal of fly ash excluded.

Construction labor shortages with accompanying overtime pay incentive not considered.

TABLE 24. COMPARISON OF BASE CASE INVESTMENT REQUIREMENTS FOR FOUR FGD PROCESSES[a]

FGD process	Total capital investment, $	$/kW
Limestone slurry	28,596,000	57
Limestone-gypsum	25,669,000	51
Chiyoda	40,531,000	81
Dowa	24,394,000	49

a. Basis

500-MW new coal-fired power unit.
3.5% sulfur in coal.
90% SO_2 removal.
Onsite disposal of limestone sludge.
Mid-1977 cost basis.

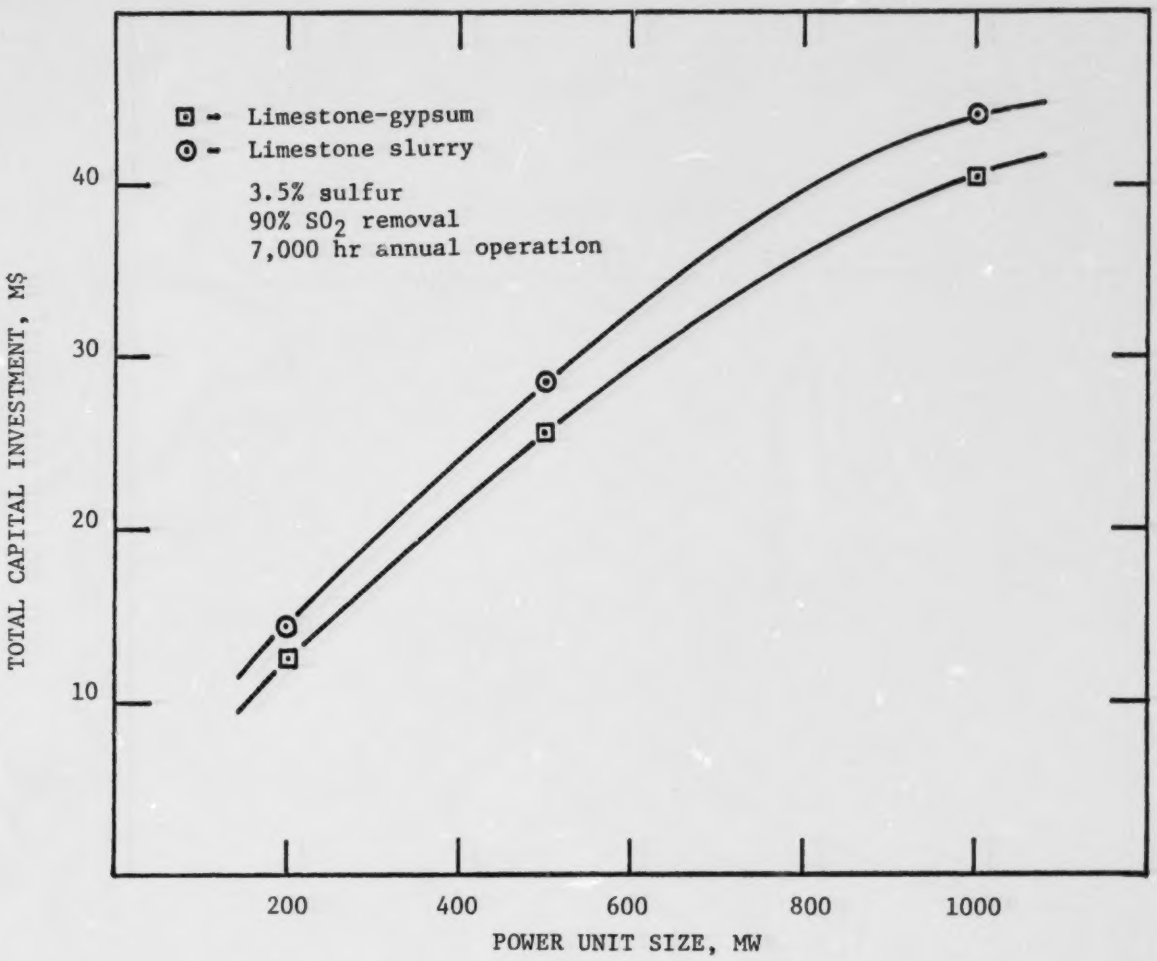

Figure 15. Limestone slurry and limestone-gypsum processes. Effect of power unit size on total capital investment.

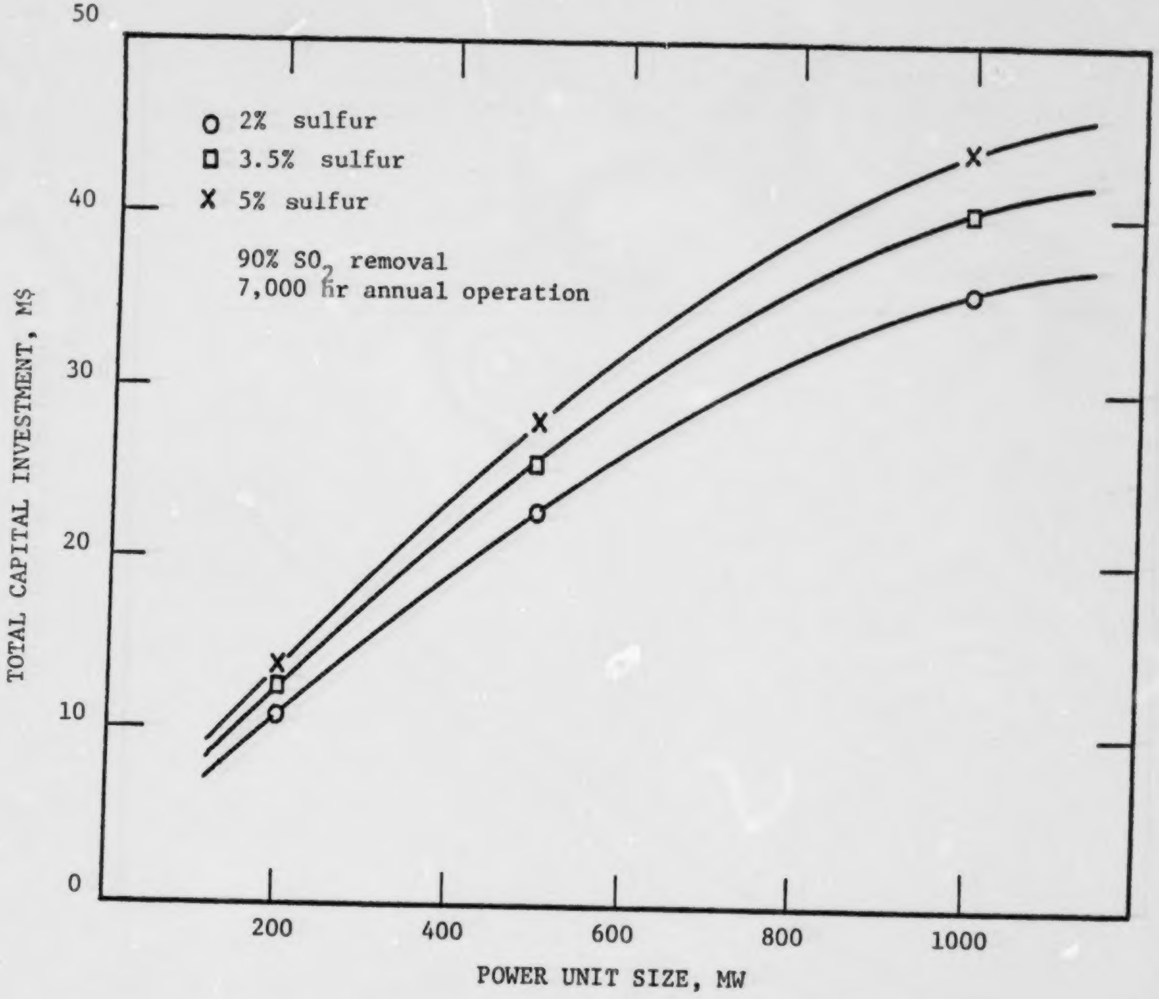

Figure 16. Limestone-gypsum process. Effect of power unit size and percent sulfur on total capital investment.

TABLE 25. LIMESTONE SLURRY PROCESS

TOTAL AVERAGE ANNUAL REVENUE REQUIREMENTS - REGULATED UTILITY ECONOMICS[a]

(500-MW new coal-fired power unit, 3.5% sulfur in fuel, 90% SO_2 removal, onsite solids disposal)

	Annual quantity	Unit cost, $	Total annual cost, $	% of total annual revenue requirement
Direct Costs				
Delivered raw materials				
Limestone	175.0 ktons	6.00/ton	1,050,000	10.39
Subtotal raw materials cost			1,050,000	10.39
Conversion costs				
Operating labor and supervision	21,380 man-hr	10.00/man-hr	213,800	2.11
Utilities				
Steam	518,000 klb	1.40/klb	725,200	7.18
Process water	250,300 kgal	0.11/kgal	27,500	0.27
Electricity	55,731,000 kWh	0.027/kWh	1,504,700	14.89
Maintenance				
Labor and material, 0.08 x 18,261,000			1,460,900	14.46
Analyses			45,600	0.45
Subtotal conversion costs			3,977,700	39.36
Subtotal direct costs			5,027,700	49.75
Indirect Costs				
Average capital charges at 14.9% of total capital investment			4,260,800	42.17
Overhead				
Plant, 20% of conversion costs			795,500	7.87
Administrative, 10% of operating labor			21,300	0.21
Subtotal indirect costs			5,077,600	50.25
Total annual revenue requirements			10,105,300	100.00
	Mills/kWh	¢/MBtu heat input	$/ton coal burned	$/ton sulfur removed
Equivalent unit revenue requirements	2.89	32.08	7.70	281.64

a. Basis
Remaining life of power plant, 30 years.
Coal burned, 1,312,500 tons/year, 9,000 Btu/kWh.
Stack gas reheat to 175°F.
Power unit on-stream time, 7,000 hours/year.
Midwest plant location, 1978 revenue requirements.
Total capital investment, $28,596,000; subtotal direct investment, $18,261,000.
Working capital, $847,300.
Revenue requirements for removal and disposal of fly ash excluded.

TABLE 26. LIMESTONE-GYPSUM PROCESS

TOTAL AVERAGE ANNUAL REVENUE REQUIREMENTS - REGULATED UTILITY ECONOMICS[a]

(500-MW new coal-fired power unit, 3.5% sulfur in fuel, 90% SO_2 removal, 240,960 tons/year gypsum, 1978 cost basis)

	Annual quantity	Unit cost, $	Total annual cost, $	% of total annual revenue requirement
Direct Costs				
Delivered raw materials				
Limestone	175.0 ktons	6.00/ton	1,050,000	8.68
H_2SO_4	24.1 ktons	54.00/ton	1,301,400	10.76
Subtotal raw materials cost			2,351,400	19.44
Conversion costs				
Operating labor and supervision	28,050 man-hr	10.00/man-hr	280,500	2.32
Utilities				
Steam	526,400 klb	1.40/klb	737,000	6.09
Process water	269,000 kgal	0.11/kgal	29,600	0.24
Electricity	88,723,000 kWh	0.027/kWh	2,395,500	19.80
Water treatment	74,340 kgal	1.20/kgal	89,200	0.74
Maintenance				
Labor and material, 0.08 x 16,392,000			1,311,400	10.84
Analyses			68,400	0.57
Subtotal conversion costs			4,911,600	40.60
Subtotal direct costs			7,263,000	60.04
Indirect Costs				
Average capital charges at 14.9% of total capital investment			3,824,700	31.61
Overhead				
Plant, 20% of conversion costs			982,300	8.12
Administrative, 10% of operating labor			28,100	0.23
Subtotal indirect costs			4,835,100	39.96
Total annual revenue requirements			12,098,100	100.00

	Mills/kWh	¢/MBtu heat input	$/ton coal burned	$/ton sulfur removed	$/ton gypsum produced
Equivalent unit revenue requirements	3.46	38.41	9.22	337.18	50.21

a. Basis
Remaining life of power plant, 30 years.
Coal burned, 1,312,500 tons/year, 9,000 Btu/kWh.
Stack gas reheat to 175°F.
Power unit on-stream time, 7,000 hours/year.
Midwest plant location, 1978 revenue requirements.
Total capital investment, $25,669,000; direct investment, $16,392,000.
Working capital, $1,249,400.
Revenue requirements for removal and disposal of fly ash excluded.
Gypsum production rate and unit production cost are based on dry $CaSO_4 \cdot 2H_2O$, however, gypsum cake contains 20% free moisture.

TABLE 27. CHIYODA THOROUGHBRED 101 FGD PROCESS

TOTAL AVERAGE ANNUAL REVENUE REQUIREMENTS - REGULATED UTILITY ECONOMICS[a]

(500-MW new coal-fired power unit, 3.5% sulfur in fuel, 90% SO_2 removal,
198,800 tons/year gypsum, 1978 cost basis)

	Annual quantity	Unit cost, $	Total annual cost, $	% of total annual revenue requirement
Direct Costs				
Delivered raw materials				
Limestone	124,677 tons	6.00/ton	748,100	4.83
Catalyst, $Fe_2(SO_4)_3$	1,750 tons	85.00/ton	148,800	0.96
Subtotal raw materials cost			896,900	5.79
Conversion costs				
Operating labor and supervision	46,500 man-hr	10.00/man-hr	465,000	3.00
Utilities				
Steam	509,910 klb	1.40/klb	713,900	4.61
Process water	201,130 kgal	0.11/kgal	22,100	0.14
Electricity	155,125,600 kWh	0.027/kWh	4,188,400	27.05
Water treatment	74,340 kgal	1.20/kgal	89,200	0.58
Maintenance, 6% of direct investment (labor and material)			1,553,000	10.03
Analyses	3,500 man-hr	15.00/man-hr	52,500	0.34
Subtotal conversion costs			7,084,100	45.75
Subtotal direct costs			7,981,000	51.54
Indirect Costs				
Average capital charges at 14.9% of total capital investment			6,039,100	39.01
Overhead				
Plant, 20% of conversion costs			1,416,800	9.15
Administrative, 10% of operating labor			46,500	0.30
Subtotal indirect costs			7,502,400	48.46
Total annual revenue requirements			15,483,400	100.00

	Mills/kWh	c/MBtu heat input	$/ton coal burned	$/ton sulfur removed	$/ton gypsum produced
Equivalent unit revenue requirements	4.42	49.15	11.80	431.17	77.88

a. Basis
Remaining life of power plant, 30 years.
Coal burned, 1,312,500 tons/year, 9,000 Btu/kWh.
Stack gas reheat to 175°F by indirect steam reheat.
Power unit on-stream time, 7,000 hours/year.
Midwest plant location, 1978 revenue requirements.
Total capital investment, $40,531,000; direct investment, $25,883,000.
Working capital, $1,323,100.
Investment and revenue requirements for removal and disposal of fly ash excluded.
Gypsum production rate and unit production cost are based on dry $CaSO_4 \cdot 2H_2O$, however, gypsum cake contains 20% free moisture.

TABLE 28. DOWA BASIC ALUMINUM SULFATE-GYPSUM PROCESS

TOTAL AVERAGE ANNUAL REVENUE REQUIREMENTS - REGULATED UTILITY ECONOMICS[a]

(500-MW new coal-fired power unit, 3.5% sulfur in fuel, 90% SO_2 removal,
199,360 tons/year gypsum, 1978 cost basis)

	Annual quantity	Unit cost, $	Total annual cost, $	% of total annual revenue requirement
Direct Costs				
Delivered raw materials				
Aluminum sulfate, 57%	1,722 tons	150.00/ton	258,300	2.47
Limestone	124,677 tons	6.00/ton	748,100	7.14
Catalyst, $MnSO_4$	6,430 lb	0.065/lb	400	-
Subtotal raw materials cost			1,006,800	9.61
Conversion costs				
Operating labor and supervision	46,500 man-hr	10.00/man-hr	465,000	4.44
Utilities				
Steam	509,910 klb	1.40/klb	713,900	6.82
Process water	306,260 kgal	0.11/kgal	33,700	0.32
Electricity	93,752,600 kWh	0.027/kWh	2,531,300	24.18
Water treatment	74,340 kgal	1.20/kgal	89,200	0.85
Maintenance, 6% of direct investment (labor and material)			934,600	8.92
Analyses	3,500 man-hr	15.00/man-hr	52,500	0.50
Subtotal conversion costs			4,820,200	46.03
Subtotal direct costs			5,827,000	55.64
Indirect Costs				
Average capital charges at 14.9% of total capital investment			3,634,700	34.71
Overhead				
Plant, 20% of conversion costs			964,000	9.21
Administrative, 10% of operating labor			46,500	0.44
Subtotal indirect costs			4,645,200	44.36
Total annual revenue requirements			10,472,200	100.00

	Mills/kWh	¢/MBtu heat input	$/ton coal burned	$/ton sulfur removed	$/ton gypsum produced
Equivalent unit revenue requirements	2.99	33.25	7.98	291.62	52.53

[a] Basis

Remaining life of power plant, 30 years.
Coal burned, 1,312,500 tons/year, 9,000 Btu/kWh.
Stack gas reheat to 175°F by indirect steam reheat.
Power unit on-stream time, 7,000 hours/year.
Midwest plant location, 1978 revenue requirements.
Total capital investment, $24,394,000; direct investment, $15,577,000.
Working capital, $978,500.
Investment and revenue requirements for removal and disposal of fly ash excluded.
Gypsum production rate and unit production cost are based on dry $CaSO_4 \cdot 2H_2O$, however, gypsum cake contains 20% free moisture.

TABLE 29. COMPARISON OF ANNUAL REVENUE REQUIREMENTS FOR FOUR FGD SYSTEMS AT BASE CASE CONDITIONS[a]

FGD system	Total annual revenue requirements, $	Mills/kWh	¢/MBtu heat input	$/ton coal burned	$/ton sulfur removed	$/ton gypsum produced	Gypsum produced, tons/yr
Limestone slurry	10,105,300	2.89	32.08	7.70	281.64	-	
Limestone-gypsum	12,098,100	3.46	38.41	9.22	337.18	50.21	240,960
Chiyoda	15,483,400	4.42	49.15	11.80	431.17	77.88	198,800
Dowa	10,472,200	2.99	33.25	7.98	291.62	52.53	199,360

[a] Basis
500-MW new coal-fired power unit.
3.5% sulfur in coal.
90% SO_2 removal.
7,000-hour/year operation.
Mid-1978 cost basis.
Onsite disposal of limestone sludge.

Figure 17 shows the effect of power unit size on average annual revenue requirements for both limestone slurry and limestone-gypsum processes. A 200-MW power unit equipped with limestone-gypsum FGD requires revenue of $5,488,000 when operating at a load factor of 7000 kWh/kW, while a 1000-MW power unit will require $21,243,600 for the same load factor.

The effect of power unit size and sulfur content of coal on revenue requirement expressed in mills/kWh is shown in Figure 18 for limestone slurry and Figure 19 for limestone-gypsum.

The sensitivity of revenue requirements for both the limestone slurry and limestone-gypsum processes to variations in limestone price ranging from $4 to $8/ton at various power unit sizes is indicated in Figure 20.

Figure 21 shows the difference between the revenue requirements of limestone slurry and limestone-gypsum in dollars per ton of gypsum produced at various power unit sizes and sulfur contents of coal. The revenue requirements are for 7000 hours of operation and byproduct revenue is excluded from the total requirements.

Lifetime Revenue Requirements

The lifetime operating profiles over 30 years for a base case power plant with limestone slurry scrubbing (no salable abatement product) and with limestone-gypsum scrubbing including revenue from the sale of gypsum are shown in Appendix B, Tables B-9 through B-15. The overall net increase or decrease in cost of power is shown for each year, considering the declining annual revenue requirement and the net sales revenue resulting from sale of marketable gypsum.

A summary of levelized increase or decrease in unit revenue requirement equivalent to the discounted process cost over the life of the power unit appears in Table 30. For each of the processes studied, units are expressed in $/ton of coal burned, mills/kWh, ¢/MBtu heat input, and $/ton of sulfur removed. The lifetime economic projections show that gypsum must sell for about $7/ton to equate the net revenue requirements for the limestone-gypsum process to that of the limestone slurry process.

ESTIMATE LIMITATIONS

The economic evaluations of the four FGD systems presented in this report are based on premises developed for a TVA/EPA publication entitled Detailed Cost Estimates for Advanced Effluent Desulfurization Processes. Recently, design and economic premises for use in future TVA evaluations have been modified through discussion with EPA and others to reflect prevailing fuel characteristics, current design practice, and economic conditions. The results of these modifications are shown in a paper presented at the EPA Flue Gas Desulfurization Symposium in Hollywood, Florida, November 8-11, 1977 (39) where investment for the limestone

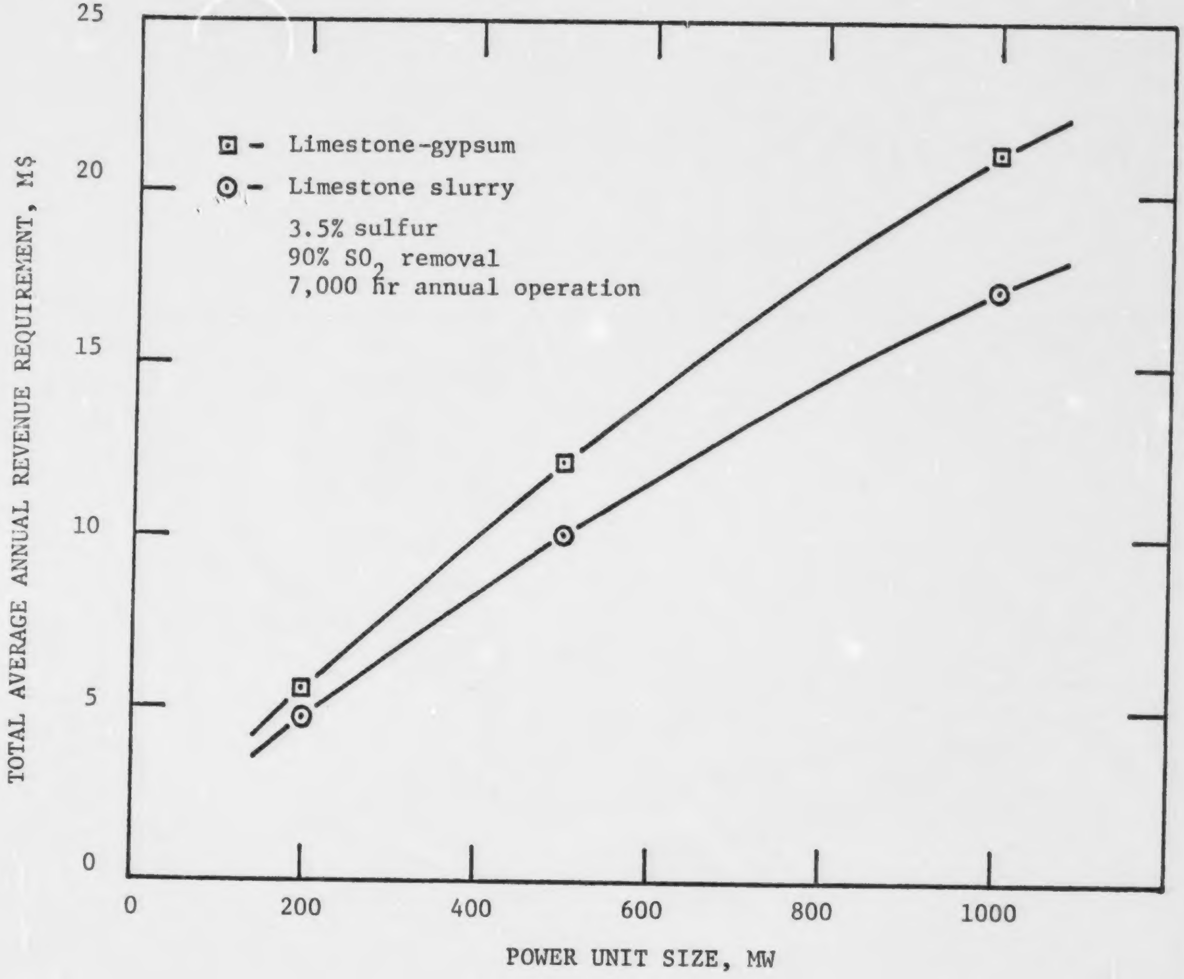

Figure 17. Limestone slurry and limestone-gypsum processes. Effect of power unit size on average annual revenue requirement.

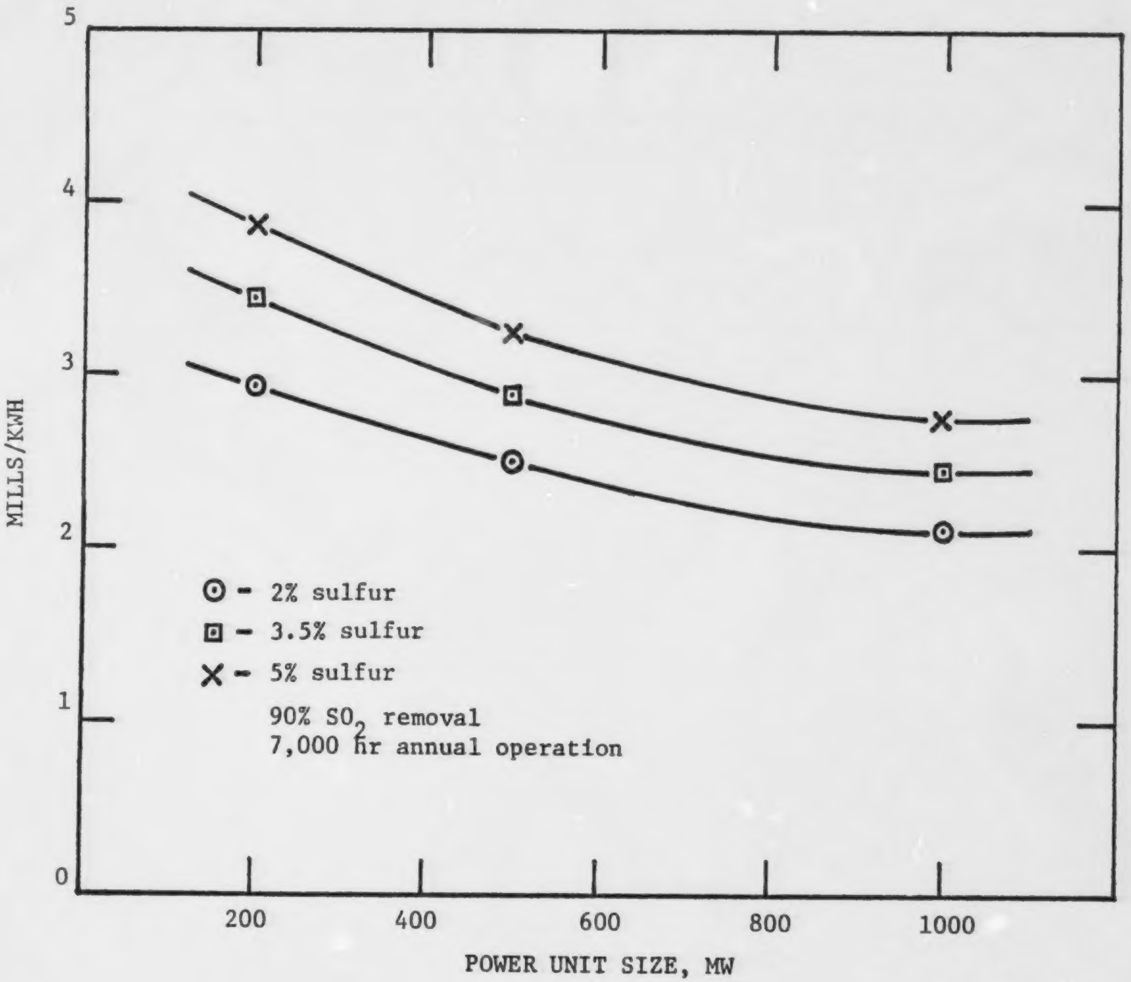

Figure 18. Limestone slurry process. Effect of power unit size and percent sulfur on revenue requirements in mills/kWh.

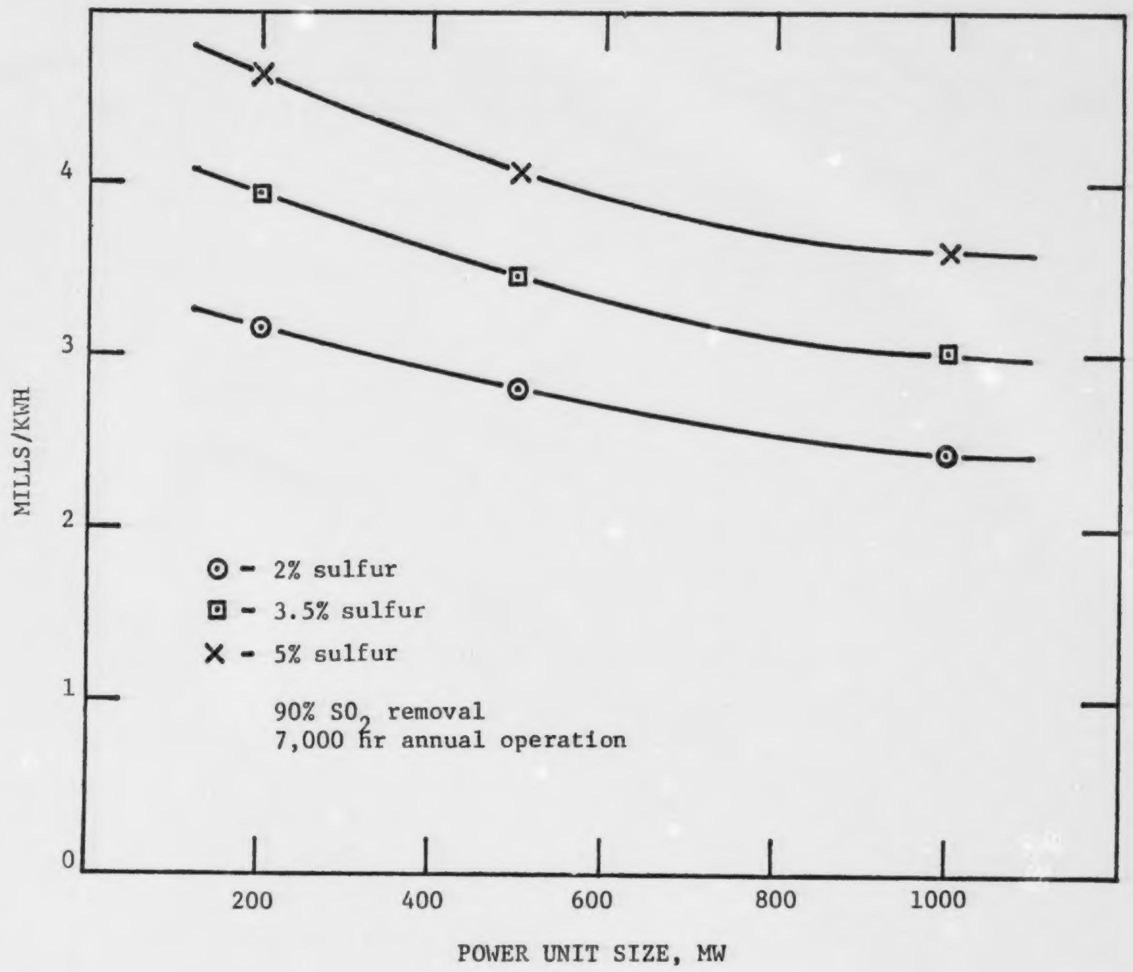

Figure 19. Limestone-gypsum process. Effect of power unit size and percent sulfur on revenue requirements in mills/kWh.

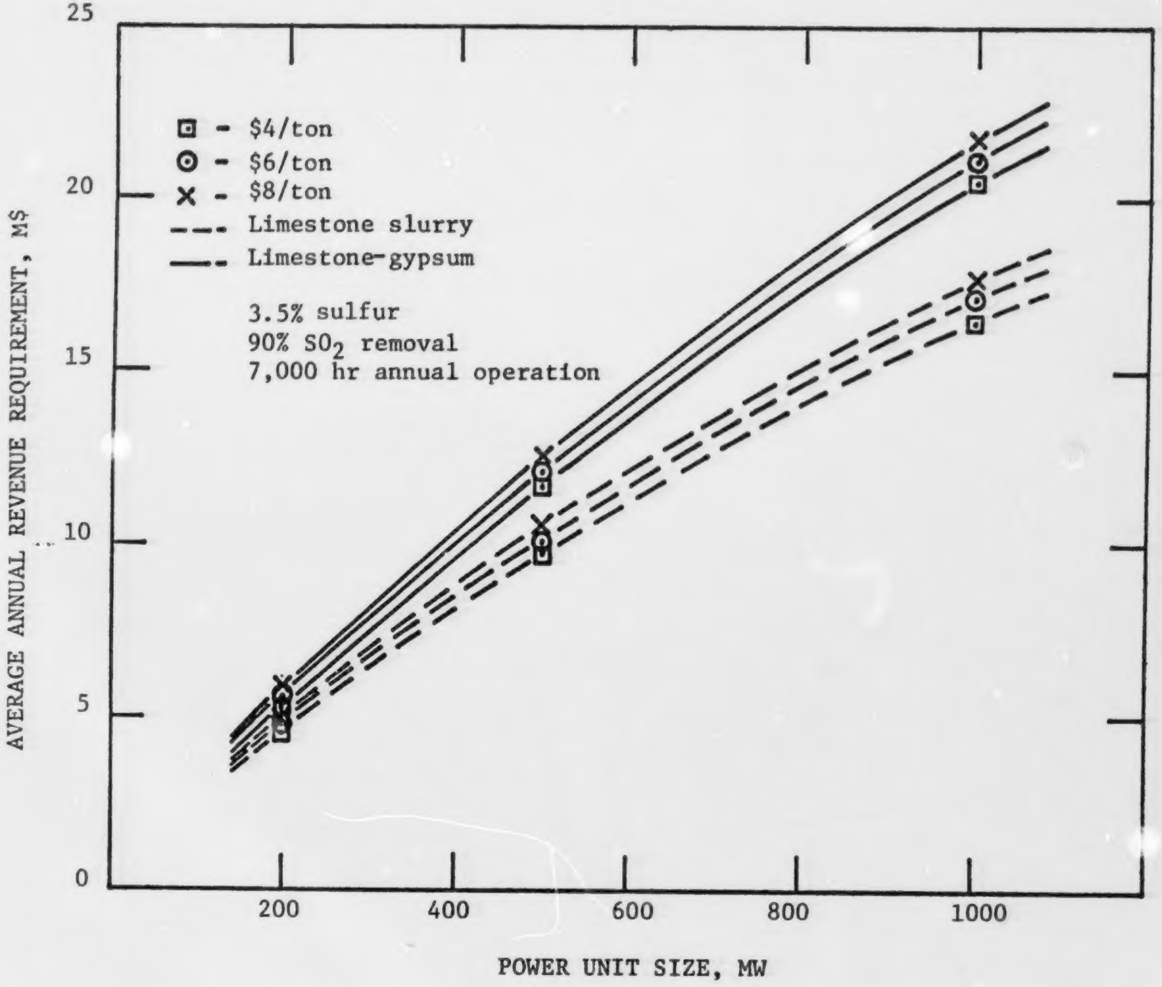

Figure 20. Limestone slurry and limestone-gypsum processes. Effect of power unit size and limestone cost on average annual revenue requirement.

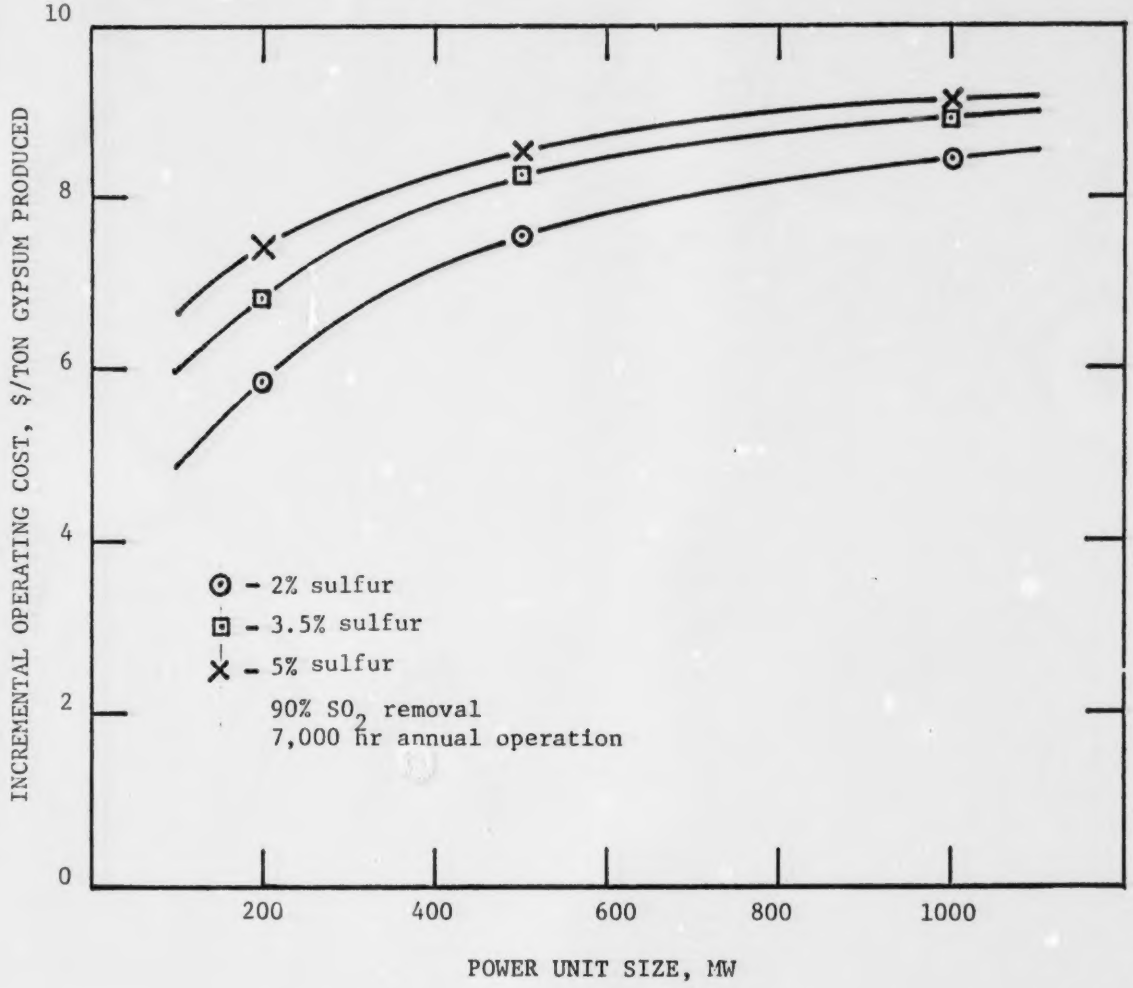

Figure 21. Differential revenue requirement between limestone slurry and limestone-gypsum. Effect of power unit size and percent sulfur on incremental revenue requirements. Byproduct revenue excluded from total revenue requirements.

TABLE 30. SUMMARY OF LIMESTONE SLURRY AND LIMESTONE-GYPSUM LEVELIZED UNIT REVENUE REQUIREMENTS

		Levelized increase (decrease) in unit revenue requirement (discounted process cost over life of power unit)			
Process	Net revenue, $/ton	$/ton coal burned	Mills/kWh	¢/MBtu heat input	$/ton sulfur removed
Limestone slurry	0.00	9.69	3.64	40.39	354.50
Limestone-gypsum	0.00	11.01	4.13	45.89	402.81
Limestone-gypsum	2.00	10.65	3.99	44.36	389.39
Limestone-gypsum	4.00	10.28	3.86	42.83	375.96
Limestone-gypsum	6.00	9.91	3.72	41.31	362.54
Limestone-gypsum	8.00	9.55	3.58	39.78	349.11
Limestone-gypsum	10.00	9.18	3.44	38.25	335.69

slurry process is estimated at $97/kW (1979) as compared with the $57/kW (1977) reported in this study. This increase of $40/kW includes not only inflation factors from 1977 to 1979 and the effects of premise changes, but also increased equipment and sludge pond requirements and a more detailed method of estimating indirect investment costs. The revenue requirements for the limestone slurry process have increased to 4.03 mills/kWh (1980) from the 2.89 mills/kWh (1978) reported here.

TVA will soon be revising the Dowa evaluation on the basis of the updated premises to produce investment and revenue requirement costs comparable to the 1979-1980 limestone slurry numbers. A new Chiyoda estimate will also follow, based on that company's latest process technology--the Thoroughbred 121 system. New technology which is an extension of Dr. Robert Borgwardt's work in forced oxidation (41) is being developed at TVA's Shawnee Test Facility. Any future estimate of a limestone-gypsum system would incorporate forced oxidation in the process design.

Although the costs of the gypsum-producing processes discussed in this study will increase using the premises and estimating techniques mentioned above, cost relativity is expected to remain approximately the same. It is unlikely that the higher estimates for the processes will affect the overall conclusions. However, caution should be exercised in reviewing this or any cost estimate to determine design parameters and premise assumptions before making direct comparisons to other evaluations.

SUPPLY OF ABATEMENT GYPSUM

According to data available from the FPC Form 67 Data Tapes, a total of 800 plants with 3,382 boilers having a total megawatt capacity of 411,404 MW will be in operation in 1978. Characteristics of the power utility industry are shown in Appendix C. For each plant considered, compliance status in 1978 was determined based on projected operating conditions and emission regulations effective June 30, 1976. SO_2 emission regulations and the method of their application in this study are shown in Appendix D. When calculated SO_2 emissions exceed calculated allowable emissions by 10% or more, the plant (or boiler) was considered to be out of compliance. According to the calculations, a total of 187 plants will be out of compliance in 1978. These plants are shown in Figure 22.

In order to provide an option for plants with extremely high estimated scrubbing costs, it was assumed that coal with sulfur content sufficiently low to meet the emission regulation could be purchased and used at an incremental premium cost of $0.70/MBtu heat content. Determination of actual costs to modify plants and purchase complying fuel was beyond the scope of this study. When the $0.70/MBtu clean fuel screen was applied, 116 plants were found to be candidates for an FGD system. A scrubber cost generator model was designed to estimate the cost of compliance by alternative scrubbing methods. A description of the model and its use is shown in Appendix E. The following analysis focuses on selection of the best candidates for gypsum production.

TOTAL POTENTIAL SUPPLY

Industry supply is based on the assumption that all plants must meet compliance and that, as in the base case, the limestone slurry process is the least costly method to use for compliance. (All plants where clean fuel would be used have already been excluded from the analysis.) Utilities would only be willing to produce gypsum and offer it for sale if the price offset the added cost of gypsum production over the limestone slurry FGD cost. The industry supply schedule therefore represents the incremental cost of gypsum production at each plant. Since the study is conducted under the long-run supply framework, the utility manager may view each process as fixed and decide which process to use before committing resources. The decision to use the gypsum-producing process therefore would be made only if total revenue from gypsum sales would at least offset the total cost difference in producing

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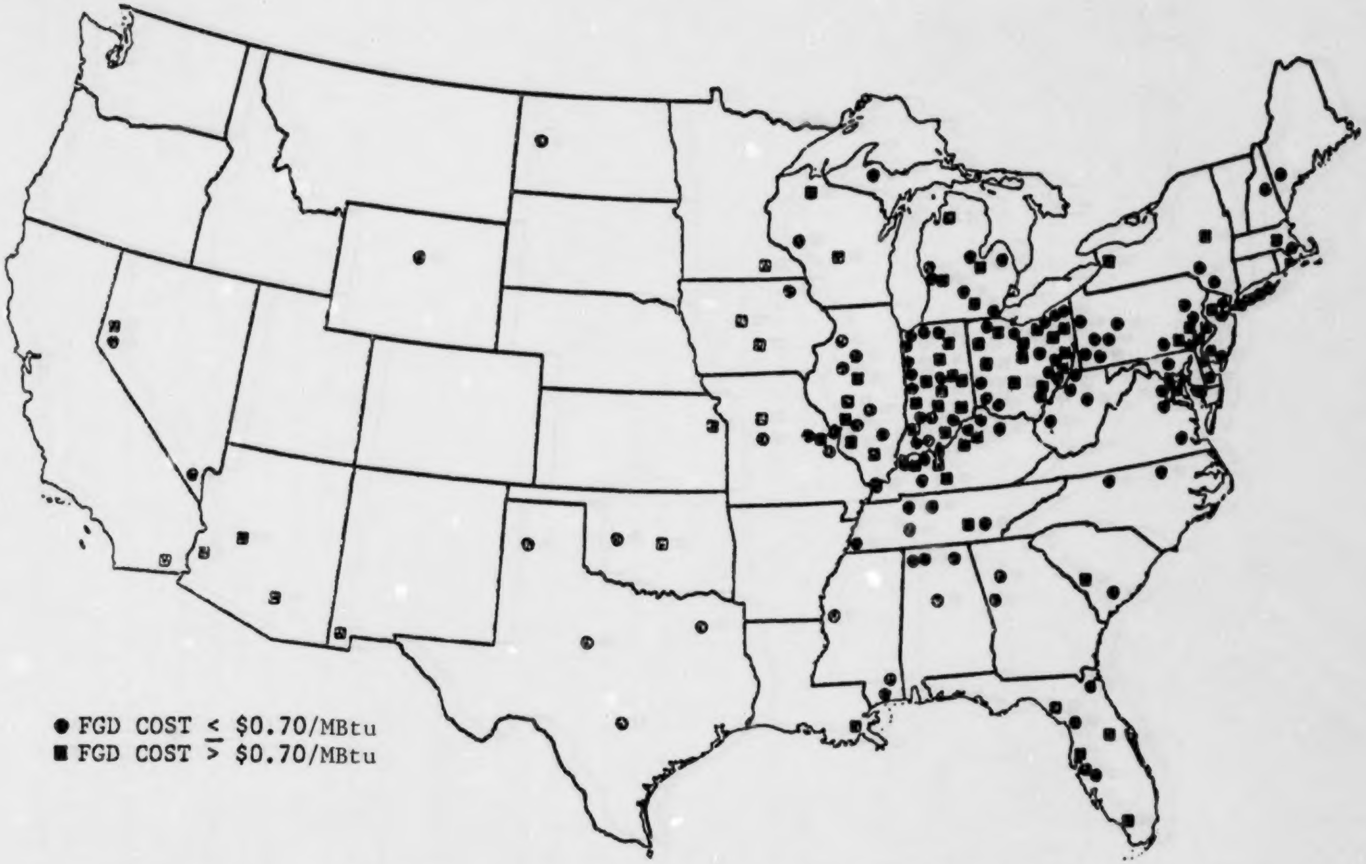
● FGD COST ≤ $0.70/MBtu
■ FGD COST > $0.70/MBtu

Figure 22. Steam plant locations calculated to exceed compliance regulations, 1973.

gypsum. Supply is committed in advance from each plant. It will either be zero tons (use limestone slurry) or the tonnage resulting from removal of required amounts of SO_2 emissions. The base case plant, for example, showed gypsum production to cost an added $7/ton. Total production was 240,900 tons. Total incremental gypsum production cost was $1,686,300. If total revenue from the sale of the total quantity of gypsum were to equal or exceed the cost difference, the decision would be made to use the gypsum-producing process and 240,900 tons would be offered. If total revenue were below the cost difference, no gypsum would be offered. In determining total revenue from gypsum sales, the option to stockpile gypsum for future sale was left open. Stockpiling cost is assumed to be $2.40/ton. In estimating total revenue the steam plant would absorb freight cost of up to $2.40/ton. (The estimate for stockpiling cost includes direct labor, equipment charges, and land charges.)

Industry supply on a plant-by-plant basis is shown in Table 31. Market and revenue potential for each plant is covered in the next section of the analysis. Total production could amount to over 27 Mtons or about 9 Mtons more than projected for the 1978 domestic consumption. Even if all plants could produce and sell abatement gypsum at sufficient revenue to offset additional cost of production, markets would not be available for the total production.

VARIABILITY IN INCREMENTAL COST

The data in Table 31 show a variability in incremental cost of gypsum per ton ranging from a negative $13 to a positive $20/ton. Depreciation and capital charges are directly proportional to the required investment for all processes and account for the major portion of the net revenue requirements. Incremental costs for producing byproduct gypsum as opposed to ponding a limestone sludge is calculated as the difference between the projected revenue required for the two alternate processes divided by the quantity of gypsum produced.

There are three major factors which influence the revenue required for the two processes and the level of the variable incremental cost: plant size, sulfur content of fuel, and plant age (which determines the remaining life of the plant). The investment required for the gypsum-producing process is a function of the plant size and the sulfur content of the fuel. Since byproduct gypsum is assumed to be marketed rather than stockpiled, disposal facility size and costs for the gypsum alternative do not vary with plant age. In contrast, the investment required for the limestone process in which the disposal byproducts are ponded is a function of all three factors.

TABLE 31. TONS OF GYPSUM PRODUCED AT STEAM PLANTS EAST OF ROCKY MOUNTAINS AT CALCULATED LEVELS OF INCREMENTAL COST PER TON OF GYPSUM[a] COMPARED TO LIMESTONE SCRUBBING

(EACH PLANT WHERE LIMESTONE FGD COST IS <$0.70/MBTU[b])

Incremental cost, -$13	Incremental cost, -$6	Incremental cost, -$4	Incremental cost, -$3	Incremental cost, -$2	Incremental cost, -$1	Incremental cost, <$0
11,286	38,517	28,678	56,274	89,097	43,894	14,520
					106,931	85,824
					65,881	72,126
					55,370	92,233
						96,173
						6,680[c]
11,286	38,517	28,678	56,274	89,097	272,076	367,556

Incremental cost, >$0	Incremental cost, +$1	Incremental cost, +$2	Incremental cost, +$3	Incremental cost, +$4	Incremental cost, +$5	Incremental cost, +$6
73,645	76,772	164,573	277,413	230,814	53,517	278,044
15,752	101,700	170,129	275,382	555,853	212,128	268,766
69,142[c]	58,079	149,991	278,156	67,770	833,163	330,450
	120,567	134,101	326,840	475,461	616,939	529,662
	20,974	131,670	159,685		561,498	323,832
	158,711	46,917	208,842		330,948	127,909
	150,513	149,175	50,068		150,992	61,655
			237,269		210,506	205,279
					409,218	1,255,598
					68,801	387,177
158,539	687,316	946,553	1,813,654	1,329,898	3,447,710	3,768,372

(continued)

TABLE 31 (continued)

Incremental cost, +$7	Incremental cost, +$8	Incremental cost, +$9	Incremental cost, +$10	Incremental cost, +$11	Incremental cost, +$12	Incremental cost, +$13
456,490	311,535	187,477	81,749	500,602	660,900	489,555
68,247	56,413	957,636	92,990	668,309	633,913	
176,407	122,061	102,642	500,881	409,183	160,527[c]	
422,850	950,404	88,152	424,152	88,120	145,891[c]	
49,541		379,406	46,995	193,869	66,380[c]	
228,064		154,321	115,157	84,582		
550,580		61,878[c]	567,437	195,755		
1,378,537			557,981	121,007[c]		
290,772			68,544[c]			
			131,456[c]			
3,621,488	1,440,413	1,931,512	2,587,342	2,261,427	1,667,611	489,555

Incremental cost, +$14	Incremental cost, +$15	Incremental cost, +$16	Incremental cost, +$17	Incremental cost, +$18	Incremental cost, +$19	Incremental cost, +$20
176,238		55,281			17,245	17,660[c]
125,261						
301,499		55,281			17,245	17,660

Total plants: 113
Grand total gypsum: 27,406,562

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a. Rounded to nearest $1/ton.

b. Only 3 plants of the 116 out of compliance were located west of the transcontinental divide. All three were located inland (Wyoming and Nevada). Due to location near gypsum deposits it was concluded that no potential existed for abatement gypsum production at those three plants. They are therefore removed from consideration as potential gypsum suppliers and will be assumed to choose the limestone slurry process.

c. Plants where mixed strategy would be used. (One or more boilers would use a scrubbing system, remaining would use clean fuel.)

Variations in power plant size and sulfur content of fuel affect investment (and associated revenue requirements) differently for the two processes. The limestone process realizes improved economics relative to the gypsum process for larger plants and plants which utilize high-sulfur fuels because the economy of scale for building large ponds is better than for building large gypsum-producing facilities. However, for either small plants or installations which utilize low-sulfur fuel, the reverse is true.

The effect of plant age is also significant in impacting incremental costs. Since older plants have a lower remaining life, the investment required for the limestone process disposal ponds is lower for older plants. The limestone process for older plants realizes a capital investment (and revenue requirement) savings with decreasing remaining life and therefore becomes more economical than the gypsum process since the investment (and associated revenue requirements) for the gypsum process do not decrease with plant age.

The extreme cost variability occurs in only a few cases and only a small volume of required sulfur removal is involved. The base case estimate indicated an incremental cost of $7/ton for a new 500-MW plant. Results of the cost model when applied to all plants out of compliance indicated a $7/ton incremental cost on 13% of total potential gypsum production. Two-thirds of total potential production would occur within a range of $3.50 to $10.50/ton incremental cost. Only 10% of total potential abatement gypsum production would occur at an incremental cost below estimated cost of mining crude gypsum.

MARKET POTENTIAL FOR ABATEMENT GYPSUM

Fifty-five existing demand points for crude gypsum are calcining plants. These plants are estimated to use 11,855,910 tons of gypsum in 1978 including 4,770,000 tons of imported gypsum at 23 plants. Estimated consumption per plant ranges from a low of 58,260 tons to a high of over 500,000 tons. Average consumption per plant was estimated at 215,562 tons. Distribution of calcining plants by estimated annual use of crude gypsum is shown in Table 32.

TABLE 32. SUMMARY OF PROJECTED ANNUAL USE BY WALLBOARD PLANTS BY SIZE - 1978 (Eastern U.S.)

Size, ktons	No. plants
<10	-
100-200	13
200-300	34
300-400	2
>400	44

All except three of the interior calcining plants are located at or near mine sites. In these cases the delivered cost is based on $3/ton variable mining cost plus $1/ton for moving the material from mine to plant. For the three exceptions, calculated rail rates from the company-owned mines were added to the $3/ton variable cost to establish a delivered cost. For coastal plants, shipping costs of $3-5 were added to the estimated variable mining cost of $2 for imported gypsum to calculate delivered cost. The distribution of calcining plants by delivered cost of crude gypsum was as follows:

Delivered cost, $/ton	No. plants
4	24
5-7	28
8-10	3

One hundred thirty-two demand points are cement plants. The cement industry is projected to use a total of 3,187,391 tons of gypsum in 1978 including 1,164,000 tons of imported gypsum at 43 plants. Use per plant ranges from a low of 2,550 tons to a high of 65,875 tons. Average use per plant will amount to 24,147 tons. The distribution of plants by estimated annual use of gypsum is shown in Table 33.

TABLE 33. SUMMARY OF PROJECTED ANNUAL USE BY CEMENT PLANTS BY SIZE - 1978 (Eastern U.S.)

Size, ktons	No. plants
<10	8
10-20	45
20-30	46
30-40	20
>40	13

Delivered prices were based on an average f.o.b. price of $6/ton from nearest supply points. Supply points for imported gypsum were assumed to be the nearest calcining plant. Rail transportation was assumed in each case and minimum delivered cost of crude gypsum was calculated to each cement demand point. Delivered costs ranged from a low of $12.43/ton to a high of $21.18. The majority of tonnage has a delivered cost of between $15 and $18/ton. Distribution of delivered cost to cement plants is as follows:

Delivered cost, $/ton	No. plants
<15	33
15-18	78
>18	22

MARKET MODEL

The market model and methodology of the study is based on the concept that utilities can produce and distribute abatement gypsum and replace that currently being purchased by wallboard and cement plants. If the replacement gypsum can be produced and distributed to current demand points at present cost or less without adding to FGD costs for utilities, the total cost to the two industries is lower. The prediction of which steam plants would have an economic incentive to produce abatement gypsum and which demand points would have an economic incentive to purchase abatement gypsum is accomplished through use of a model. Projected demand at each point and minimum delivered cost of crude gypsum has been established. The supply of abatement gypsum at each steam plant along with total incremental gypsum production cost at each point and transportation cost to each demand point have also been established. The nature of supply is that production of gypsum will be either zero tons or the tonnage to be produced at compliance for each plant.

The model calculates total cost to the gypsum industry to mine and distribute crude gypsum and total cost to the utilities industry to meet compliance by the limestone slurry FGD system. The sum of the two costs represents total cost to both industries. All costs are established on a point-by-point basis and industry cost represents the sum of each cost at demand points or supply points. The transportation portion of the model solves for the maximum potential revenue to each utility (supply point) on a plant-by-plant basis to meet compliance by the gypsum-producing to FGD process. If total gypsum revenue minus total incremental gypsum production cost is positive on a plant basis, production and sale of abatement gypsum by the utility results in reduction in cost to both the utilities industry and the gypsum industry. If total revenue minus total incremental cost to the utility is zero, there is still an incentive production and sale of abatement gypsum since the utility avoids the problems associated with ponding slurry.

In the model, each utility attempts to produce and sell abatement gypsum in competition with all other utilities. The solution shows only the utilities that could economically produce and market abatement gypsum to existing wallboard and cement plants and assumes that those plants would choose the gypsum process; all others would choose the limestone slurry process. Further, the solution assumes that each plant produces gypsum in 1978 and that the market instantly arrives at equilibrium conditions. Such "perfect" decisions will not be made by the two industries and therefore an alternative approach to generating market solutions was utilized that reflects an analytical procedure that an individual utility might employ in assessing its potential to produce and market abatement gypsum.

MARKET ANALYSIS

The analysis is conducted in a predictive mode by using a screening procedure moving from least restrictive to more restrictive market conditions at each step. As conditions become more restrictive the number of plants that would be predicted to produce and market gypsum declines.

Maximum Noncompetitive Supply of Abatement Gypsum

The initial step is to consider each potential gypsum producer as though the supply from that plant were the only source of new supply. Each utility may supply any demand point without regard for competition for that demand. The incremental gypsum production cost, tons of gypsum to be produced, price and quantity at each demand point, and rail rate to each demand point are established. Then an f.o.b. price per ton to each demand point is developed that allows abatement gypsum to be purchased at the same cost as crude gypsum. In other words, all savings possible are captured by the utility industry. This procedure assures that all possible gypsum suppliers are considered in the best possible circumstances. If the total revenue is negative at any plant after this analysis, it could never become positive under more restrictive conditions.

An analysis was completed for each plant under the above conditions. A total of 66 utilities could reduce the cost of compliance by producing and marketing gypsum. A total of 101 nonexclusive demand points were involved in the solution. Only 2 of the 101 demand points are calcining plants, the rest are cement plants. This solution does not quantify the market, it simply illustrates that 66 utilities are potential suppliers if they each had first choice at the market.

Data from an example plant are shown in Table 34 to demonstrate information generated for each steam plant. The plant is calculated to produce a total of 158,716 tons of gypsum. The cost of the limestone slurry process is $12,685k and the cost of the gypsum-producing process is $12,831k making a total incremental cost of $146k or $0.92/ton of gypsum. Gypsum production is distributed to eight demand points as shown. The first three columns show demand point identification, current demand for gypsum, and calculated minimum delivered cost of crude gypsum to each point. The next three columns show distribution of abatement gypsum by the steam plant. Tons sold to each demand point, maximum f.o.b. price to the utility for each demand point, and revenue from each transaction are shown. Total revenue to the utility is $1,233k. Net revenue (total revenue minus $146k total incremental cost) is $1,087k. Total savings to both industries is $1,087k, all of which accrues to the utility. If the utility could effect the above transactions, the cost of compliance for that plant could be reduced by an amount equal to net revenue. The gypsum industry would replace a total of 158,716 tons of crude gypsum with abatement gypsum. There would be no savings to the gypsum industry since the utility was allowed to sell to each demand point at exactly the same price as crude gypsum.

TABLE 34. ABATEMENT GYPSUM PRODUCTION COST, DISTRIBUTION FOR CEMENT PRODUCTION, AND REVENUE - EXAMPLE PLANT

		Limestone slurry		Abatement gypsum production		Incremental cost	
FPC No.	Sulfur removed, tons	Cost, $	Sludge, tons	Cost, $	Quantity, tons	Total, $	Per ton, $
3795000350	23,622	12,685,279	135,094	12,831,364	158,716	146,085	0.92

	Crude gypsum demand		Utility sales, abatement gypsum		
Cement plant demand point	Quantity, tons	Delivered cost crude gypsum/ton, $	Quantity, tons	f.o.b. price/ton, $	Total revenue, $
1.	18,700	18.64	18,700	10.68	199,790.80
2.	13,940	18.64	13,940	10.68	148,934.86
3.	19,933	18.64	19,933	10.68	212,964.17
4.	32,130	18.64	32,130	10.22	328,240.08
5.	29,113	16.57	29,113	5.81	169,030.08
6.	27,413	17.03	27,413	4.16	114,038.08
7.	11,688	20.02	11,688	3.87	45,279.31
8.	20,698	15.50	5,799	2.63	15,251.37
Total			158,716		1,233,528.85

Such a situation would be unlikely for the utility even if it were the only abatement supplier among utilities. In order to sell the supply of abatement gypsum, the utility would have to develop a sales policy and establish a price incentive to implement that policy. These circumstances lead to the second step in the analysis. The sales objective may be to maximize net revenue from the production and sale of abatement gypsum, or it might be to dispose of as much gypsum as possible so long as cost of compliance is lower than the remaining least-cost alternative--in this case, the limestone slurry process. This balance is brought about by incurring increasing transportation cost to serve more distant markets in order to increase tonnage sold. As transportation cost increases the uniform f.o.b. price must decrease to the level required to market the desired tonnage. In order to establish quantities of abatement gypsum that can be sold from utilities in competition for the markets, an approximate equilibrium analysis is necessary.

Distribution of Abatement Gypsum at Approximate Market Equilibrium

The objective of this analysis is to establish a price f.o.b. utility that maximizes revenue while matching supply and demand. The plants with the lowest incremental costs shown in Table 31 are the plants most likely to produce gypsum when location is not considered. The nature of the pricing assumptions with respect to f.o.b. price of crude gypsum results in uniform delivered costs of crude gypsum to the demand points. The demand points are located in every major market area of the Eastern United States. Therefore, the utilities most likely to produce gypsum are the ones closest to markets and with the lowest incremental cost. The analysis is completed by first maximizing revenue to the steam plant with the lowest incremental cost. All demands fully satisfied by the first plant will be eliminated from further consideration, and the next least cost steam plant will be entered and so on until all steam plants have been considered. The solution so generated would represent an approximation of an equilibrium solution based on logical market development.

Under these conditions 30 steam plants are predicted to produce and market gypsum when all potential candidates compete for the available markets; the total amount of abatement gypsum sold was 2,399,081 tons. The 30 steam plants in the final solution, their location, production, and incremental cost per ton of gypsum are shown in Table 35. Graphical representations of supply and demand points are shown in Figures 23 and 24 respectively. The overall results of the analysis are summarized in Table 36.

TABLE 35. SUMMARY OF STEAM PLANTS CALCULATED TO PRODUCE AND MARKET ABATEMENT GYPSUM, AND NET REVENUE PER PLANT

FPC No.	State	Gypsum produced, tons	Incremental cost compared to limestone scrubbing, $/ton gypsum	Net revenue, $
1385000100	DE	11,288	-12.66	199,063
5250001000	VA	38,520	-5.56	396,425
2345000200	FL	28,677	-3.56	320,266
2270000700	IA	56,278	-2.95	488,383
3945000600	MD	89,101	-2.37	511,865
5430000250	TX	65,887	-1.44	337,968
5440000100	OK	55,371	-1.15	294,934
3080000400	MS	106,933	-0.92	912,828
0805002700	ME	43,895	-0.90	183,935
4050001150	NH	72,128	-0.32	194,889
4740000100	FL	96,176	-0.31	874,427
2920000500	MI	14,520	-0.28	84,715
4480000075	SC	92,238	-0.23	809,931
3080000150	MS	85,829	-0.23	543,275
5235000100	NJ	6,679	-0.03	42,814
4045000800	IN	69,132	0.06	427,859
4785000575	TX	73,647	0.16	331,036
5420000400	PA	15,749	0.29	167,451
1415000150	KY	101,706	0.57	388,260
3590000200	NY	20,977	0.57	146,367
2605000150	MI	58,079	0.59	327,902
0720000900	NC	76,778	0.68	393,633
3795000350	PA	158,716	0.92	342,920
5250001400	VA	150,519	1.01	328,600
0785000500	IL	170,139	1.60	569,098
2260000100	IN	134,105	2.00	101,735
3085000350	MS	131,672	2.02	205,045
0700000550	NY	164,582	2.46	492,155
4820000700	MI	50,070	3.00	46,109
3840000500	PA	159,690	3.02	612,098
Total		2,399,081		11,075,986

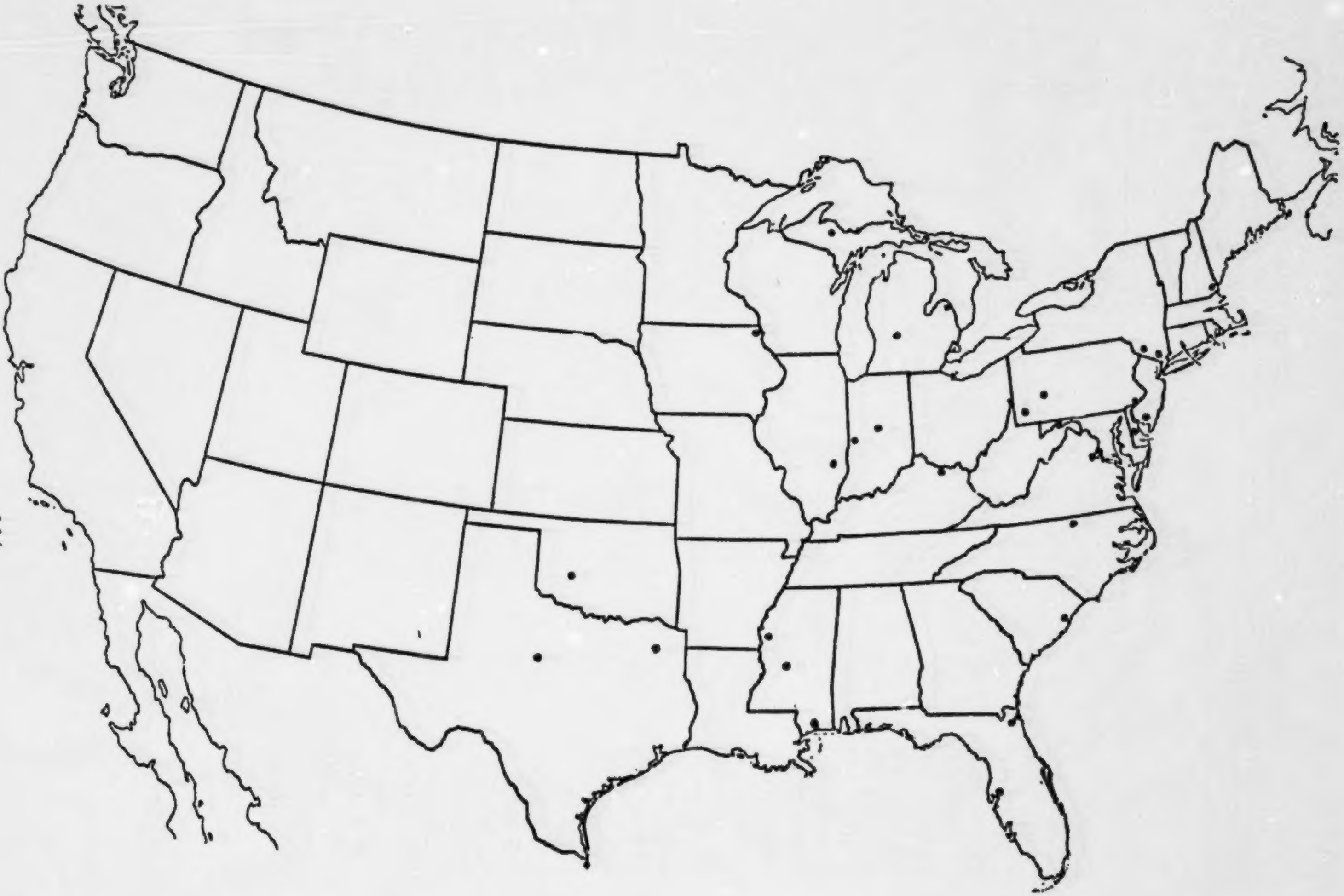

Figure 23. The locations of 30 steam plants that could lower cost of compliance by producing and marketing gypsum.

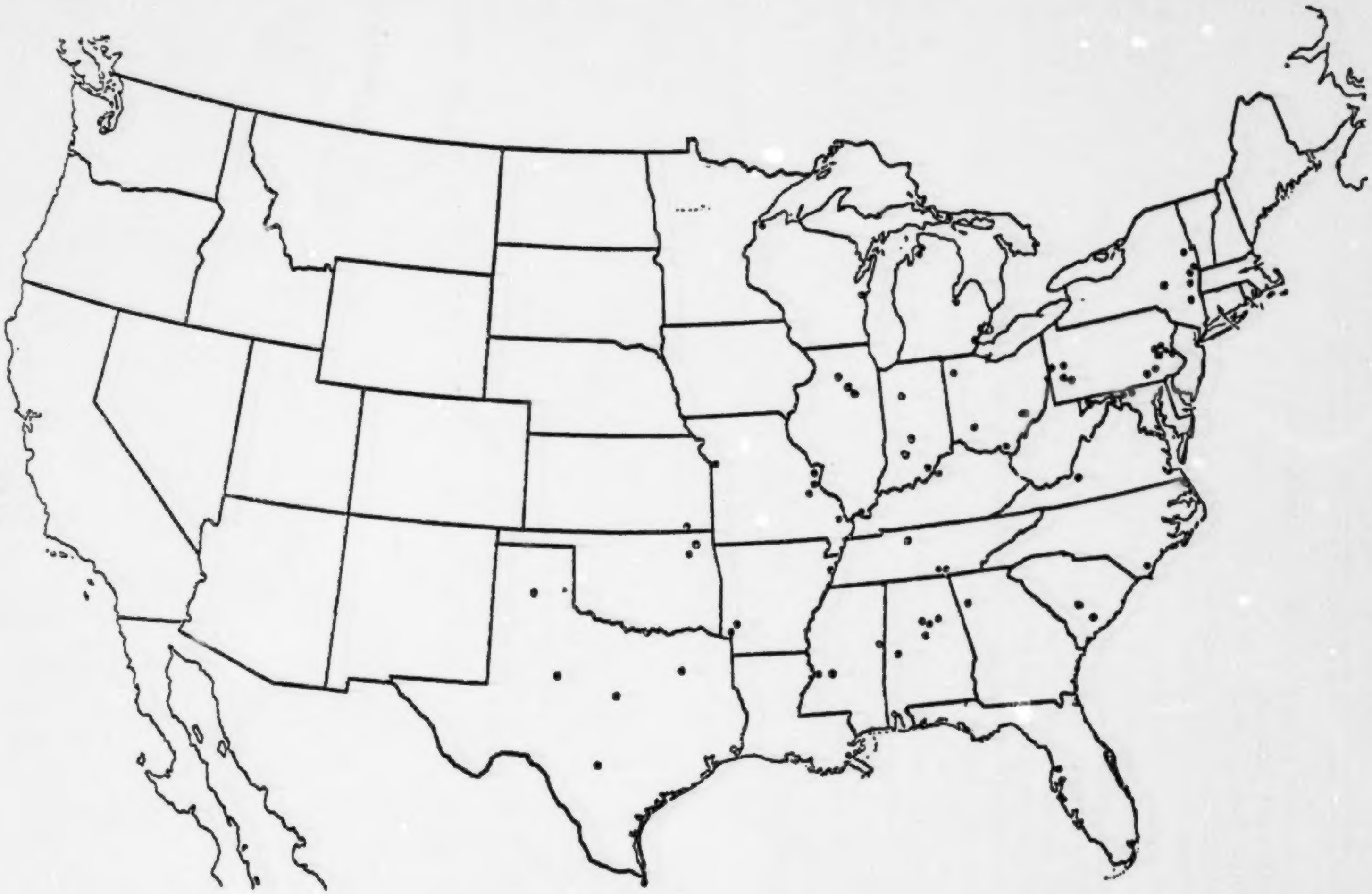

Figure 24. The location of demand points.

TABLE 36. SUMMARY OF ANALYSIS RESULTS

Total number of plants out of compliance	187
Lowest-cost strategy	
Clean fuel, number of plants	71
Limestone slurry process, number of plants	86
Gypsum production and marketing, number of plants	30
Total gypsum produced, tons	2,400,000
Average production per steam plant, tons	80,000
Smallest gypsum supplier, tons	6,700
Largest gypsum supplier, tons	171,000
Total gypsum sold, tons	2,230,000
Total gypsum stockpiled, tons	171,000
No. of plants where part of production was stockpiled	5
Wallboard plants served	1
Cement plants served	92
Sold to wallboard plants, tons	95,000
Sold to cement plants, tons	2,135,000
Total net revenue to utilities, $	11,076,000
Total savings to gypsum industry, $	1,900,000
Savings to gypsum industry, % of total cost	1.5
Average savings per ton of gypsum purchased, $	0.86
Total first-year compliance cost for 113 plants using the limestone slurry process, $	2,038,000,000
Reduction by marketing gypsum, $	11,076,000
Cost reduction, %	0.5
Required sulfur removal, tons	4,109,000
Sulfur removed by gypsum process, %	8.7
Reduction in sludge disposal by limestone slurry, %	8.0
Imported gypsum displaced, tons	856,000
Domestic gypsum displaced, tons	1,372,000
1978 calcining market served with abatement gypsum, %	0.8
1978 cement market served with abatement gypsum, %	67.0

The results of the market analysis summarized in Table 36 indicate a limited potential for abatement gypsum production and marketing to significantly contribute to solving compliance problems faced by the nation's utilities. The original scope of the project was to assess the feasibility of replacing the crude gypsum projected to be consumed in wallboard manufacturing in 1978. The analysis indicates that abatement gypsum would be used by only one existing wallboard manufacturing plant. This is a result of more profitable markets in the cement industry. For example, two plants in Florida are located near wallboard manufacturing plants. If cement markets were not available, these two plants could partially supply the needs of the wallboard plants on a mutually profitable basis.

The major potential for abatement gypsum marketing is to supply the cement industry. In the analysis 2,132,900 tons was calculated to be supplied to 92 plants in the cement industry. This tonnage represents 67% of the projected 1978 consumption of gypsum by the cement industry in the eastern portion of the United States. This tonnage was provided by small abatement producers that could supply requirements of cement plants located near the utility. Fifteen of the 30 utilities in the final solution actually were calculated to have lower cost of gypsum production than for the limestone slurry throwaway product. An additional seven plants had an incremental cost of less than $1/ton of gypsum. The average annual production at these steam plants was 65,400 tons.

The analysis was based on conservative estimates of gypsum mining costs, but in all other respects the analysis was based on premises favorable to abatement gypsum. It was assumed to be a perfect substitute and that users would purchase abatement gypsum instead of crude if it is available at the same price. Two specific disadvantages for abatement gypsum were identified: the product has 20% free moisture, and it may present mechanical handling problems. Extra costs to the gypsum industry to overcome these disadvantages were not quantified, but to the extent that they present real costs to the gypsum industry, the added costs would be discounted from value attributed to abatement gypsum. When average savings per ton to the gypsum industry are only $0.86/ton, the economic incentive may not justify the risk of substitution.

The analysis indicates that 74% of imported material used by the cement industry would be replaced. Since the transportation cost for the imported material makes up such a high percentage of its total value, the possibility for replacement with local supplies of abatement gypsum is good.

Characteristics of steam plants are shown in Table 37 and compared with characteristics of the plants calculated to produce and market abatement gypsum.

TABLE 37. SUMMARY OF PROJECTED STEAM PLANT CHARACTERISTICS, 1978

	1978 all U.S. plants	1978 plants out of compliance	Calculated least-cost compliance strategy		
			Clean fuel	Limestone FGD	Gypsum FGD
No. of power plants	800	187	71	86	30
No. of boilers	3,382	833	376	357	100
Total capacity, MW	411,004	132,599	23,081	86,628	22,890
Fuel use					
Coal					
ktons	475,570	226,780	13,167	186,887	26,726
TBtu[a]	10,408	5,125	298	4,210,000	617,000
Average sulfur content, %	2.12	2.81	2.87	2.91	2.06
Oil					
kbbl	620,247	110,167	13,974	43,708	52,485
TBtu	3,827	687	89	271,000	327,000
Average sulfur content, %	0.99	1.42	1.50	1.51	1.23
Gas					
Cft^3	2,556	108	80	15,000	13,000
TBtu	2,602	117	82	21,000	14,000
Average capacity factor, %	31.87	35.12	20.90	40.14	42.17
Average boiler generating capacity, MW	122	159	61	242	228
Age of boilers, %					
0-5	5	10	3	11	29
6-10	8	10	6	14	12
11-15	8	6	5	7	9
16-30	42	42	38	46	40
30	37	32	48	22	10
Size of boilers, %					
200	82	75	95	59	60
200-500	11	15	4	25	22
501-1000	6	9	1	14	0
1000	1	1	0	2	0
Capacity factor of boilers, %					
20	40	35	57	17	15
20-40	20	17	24	10	20
41-60	23	29	14	38	52
60	17	19	5	35	13
Average sulfur removed per plant, tons	-	-	4,662	43,628	11,900

a. T = one trillion.

The data in Table 37 tend to confirm the predicted results of the cost model discussed in the section on variability in scrubbing cost. Plants calculated to produce gypsum are smaller than plants that would use the limestone slurry throwaway process. On the average, the annual output of sulfur is only about one-fourth as much as for limestone systems. In general, the gypsum-producing plants are newer plants, 29% of them are between zero and 5 years old compared with 11% for limestone systems. In addition, the sulfur content of fuel is lower.

Distribution Limited to Calcining Plants

Further analyses were conducted to predict market potential under changed markets or price situations. The original intent of the study was to determine feasibility of gypsum production and marketing to the wallboard products industry. One analysis was conducted in which the existing wallboard-producing plants were assumed to be the only available market outlets for abatement gypsum. Under this situation, a total of nine utilities could lower cost of compliance by producing and marketing abatement gypsum; the plants are shown in Table 38. These nine utilities would partially meet gypsum requirements of eight calcining plants. Six of the eight calcining plants are located on the east and southern coastline and currently use imported material. The other two are assumed to ship domestically-mined gypsum from company-owned mines to calcining plants--one located in Memphis, Tennessee, and one at Rotan, Texas. Two of the utilities would have to accept a negative net back of $3.42/ton. Even so, their cost would be less than utilizing the limestone throwaway system. The remaining seven would realize positive prices ranging from $0.45/ton to $3.58/ton. Total gypsum sales amount to 608 ktons.

TABLE 38. SUMMARY OF STEAM PLANTS CALCULATED TO PRODUCE AND MARKET ABATEMENT GYPSUM TO WALLBOARD PLANTS ONLY

FPC No.	State	Gypsum produced, tons
1385000100	DE	11,288
5250001000	VA	38,520
2345000200	FL	28,677
5430000250	TX	65,887
5440000100	OK	55,371
3080000400	MS	106,933
4740000100	FL	96,176
4785000575	TX	73,647
3085000350	MS	131,672

Distribution to Cement Plants with Price Reduction

The primary analysis was based on the assumption that the gypsum industry would attempt to hold the price of crude gypsum sold to the cement industry at $6.00/ton. Variable cost of mining was estimated at $3.00/ton and it could be possible that domestic crude gypsum price would decline to that level in the face of competition with abatement gypsum production by utilities. An analysis was conducted to determine the impact of a $3.00/ton decrease in price of crude gypsum. It was found that even with the $3.00/ton price decrease, 27 utilities would continue to produce and market abatement gypsum. This compares with 30 utilities in the original solution. Abatement gypsum sales would only be reduced by 365 ktons. Reduction in compliance cost would fall from $11M to $6.2M. This would be the major impact of the price reduction. The original market solution is stable even with the $3.00/ton reduction in competitive price of crude gypsum to cement plants because of their locations. The cement plants found to purchase gypsum were for the most part purchasing crude gypsum that had been imported. Utilities located in reasonable geographic proximity to these plants could displace the crude gypsum because of savings in transportation costs.

Potential New Calcining Plant Supply of Abatement Gypsum

Earlier discussion of the existing gypsum industry pointed out that wallboard plants are now located in the proximity of mines or seaports to minimize the cost of crude gypsum transportation. Producing districts were shown to exist in many states with the exception of the Southeast. The discussion of the current industry structure indicated that the control of gypsum reserves might be an effective barrier to entry into the wallboard products manufacturing industry. The availability of abatement gypsum would substantially lower barriers to entry in the eastern portion of the United States. Based on the existing industry the minimum economic size of new wallboard plants would require at least 200 ktons gypsum annually. This information suggested that there was a potential for new wallboard plants to be built across-the-fence from utilities that could supply a minimum of 200 ktons product annually. Eighteen steam plants, in addition to the thirty already in the solution, have estimated potential capacity to produce between 200 and 400 ktons gypsum annually. These plants are listed in Table 39. Incremental production costs for production of gypsum instead of using limestone scrubbing are compared to calculated minimum delivered cost of crude gypsum to the utility location based on a price of $3/ton f.o.b. mine. It is not suggested that all of these plants have a potential to develop across-the-fence outlets, but they are listed to suggest priority for more detailed analysis.

TABLE 39. LOCATION OF STEAM PLANTS WITH POTENTIAL ANNUAL GYPSUM PRODUCTION BETWEEN 200 AND 400 KTONS

FPC No.	State	Gypsum produced, tons	Incremental cost compared to limestone scrubbing, $/ton gypsum	Crude gypsum delivered, $/ton
0785000100	IL	277,421	2.52	14.72
4530000850	TX	208,853	2.63	13.80
5540000250	MO	237,275	2.66	14.73
1000000050	TX	275,392	2.82	14.26
1115001100	IL	278,167	3.25	14.03
1395000250	NC	230,825	4.03	13.57
0790000100	IL	212,139	4.96	13.57
3550000600	WV	330,958	5.02	14.72
5125000700	MO	387,189	5.50	14.72
3455000100	IN	268,773	5.98	13.81
4770000905	AL	205,286	6.20	16.79
2730000600	NY	278,052	6.40	11.66
4045001150	IN	323,842	6.43	12.88
3455000400	IN	330,461	6.49	13.81
4805000300	OH	290,785	6.50	14.72
2755000600	KY	228,070	7.02	12.42
0410000050	KY	311,547	7.54	13.11
4770000100	TN	379,422	9.35	14.95

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This analysis has been based on projected 1978 prices, costs, and operating characteristics of utilities. It has assumed that any plant out of compliance with existing air quality regulations must be in compliance in 1978. The lime-limestone throwaway process has been viewed as the least cost route to follow without revenue considerations for marketable byproducts. These assumptions allow analysis of byproduct marketing feasibility on cost differences between the lime-limestone throwaway process and the gypsum-producing process. Abatement gypsum production and marketing is assumed to be a superior alternative to the throwaway process if predicted revenue from its sale is equal to or exceeds the cost difference required to achieve compliance by the gypsum-producing process. Estimated delivered cost of crude gypsum to existing demand points is used to calculate revenue potential from abatement gypsum.

The analysis was conducted in such a manner that savings to the gypsum users could be calculated along with lowered cost of compliance to the utility industry. The final market solution predicted that 30 steam plants could lower cost of compliance by producing and marketing gypsum. These 30 plants would serve a total of 93 demand points. Only one wallboard plant would purchase abatement gypsum (partly because cement plants offer a higher price outlet). Compliance cost would be reduced in the first year by \$11M to the 30 power plants compared to use of limestone scrubbing. This amounts to an average savings of over \$350k/plant. In terms of total industry cost of compliance, the savings by gypsum production would amount to less than 1%. Savings to the gypsum industry are calculated to equal \$1M. Total gypsum production is 24 Mtons with an average production of 80 ktons/plant. The total is approximately 53% of the amount that could be produced and sold (at \$3/ton) with costs lower than limestone scrubbing.

Use of gypsum-producing technology at the 30 power plants would solve only 8.7% of the electric utility sulfur oxides compliance problem and reduce the required ponding of calcium solids by 8.0%.

Abatement gypsum would be purchased by 92 cement plants. Abatement gypsum would replace 67% of the projected use of crude gypsum by cement plants. Cement plants were projected to import 1.1 Mtons. Production from the 30 steam plants would replace 74% of the imported material used in cement plants.

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The market model was also used to assess the feasibility of gypsum production and marketing if wallboard plants were the only effective market outlets for abatement gypsum. Under this condition, only nine utilities could reduce compliance costs by producing and marketing abatement gypsum to the wallboard industry. These 9 plants could produce and market a total of 608,000 tons of abatement gypsum on an average of 67,500 tons/plant. Total reduction in compliance cost for the 9 plants in comparison to the limestone throwaway system would amount to $1.6M or an average of $184k/plant. The reason that the wallboard market is so limited is that existing plants are built at the same location as the gypsum mine or at the point of minimum water transportation costs. Cement plants, on the other hand, are not located at gypsum mines and a high percentage of the cost of crude gypsum is transportation cost rather than product cost.

An analysis was conducted based on a $3/ton price reduction to cement plants. Under this lower price assumption, 27 utilities could still reduce compliance costs by producing and marketing abatement gypsum. This compares to 30 utilities found under conditions projected for 1978. The reduction in abatement gypsum sold would amount to 365 ktons. Under the reduced price assumption, the major difference in outcome of the analysis was that savings in compliance cost for power companies was reduced from $11M to $6.2M.

Production and marketing of abatement gypsum to the cement industry appears to offer an opportunity for steam plants with low annual volumes of sulfur removal to lower cost of compliance. There appears to be little opportunity to lower compliance cost by marketing abatement gypsum to the existing wallboard products industry. The gypsum-production alternative appears to offer only a limited potential to solve the utility compliance problems; however, in terms of a total program of byproduct marketing, the gypsum-production alternative may fill a specific role in that it appears to meet the needs of small plants when other byproducts may be better suited to large plants.

Important conclusions from the study are summarized below.

1. Because of huge reserves, no major national interest would be served by subsidizing abatement production to serve as a stockpile for later use.

2. Gypsum production and marketing offers a limited potential to the utility industry to lower cost of compliance; only about 8% of the electric utility compliance problem would be solved by this method. Production cost relative to throwaway use of limestone scrubbing is too great for large plants which contribute the major share of SO_2 emissions. Incremental cost of producing gypsum is greater than the estimated mining costs for natural gypsum on approximately 85% of total possible abatement production. Only about half of the gypsum that could be produced and sold (at a price of $3) with costs lower than limestone scrubbing was marketed.

3. Gypsum production and marketing appears to be a viable alternative for relatively new plants where required SO_2 removal amounts to 20-30 ktons of sulfur annually.

4. When viewed in a total program of byproduct production and marketing, gypsum takes on added significance in that it is particularly well-suited to the segment of the industry with a small annual volume of required sulfur removal.

5. Cement plants offer the greatest potential market outlet for abatement gypsum; the wallboard industry would provide an extremely limited market. The demand at cement plants averages 25 ktons/plant and offers the possibility for about 30 steam plants to locate a few local market outlets for abatement gypsum.

6. Abatement gypsum appears to offer fewer problems in the manufacture of cement than in wallboard.

7. Price reaction by gypsum producers cannot be predicted, but 27 steam plants would be predicted to continue to produce and market abatement gypsum to the cement industry in the face of a $3/ton price reduction.

8. Stability of the solution may be further ensured since such a high proportion of the abatement market is gained by replacing imported gypsum.

9. Agricultural use of gypsum represents a minor part of the total market. If forecasts of increasing soil sulfur deficiencies are correct, agricultural use will be a potential growth market for sulfur products, including gypsum.

In addition to the primary results, other specific accomplishments were generated by the study.

1. Specific supply and demand data bases for crude gypsum were established and may be maintained or improved.

2. A computerized system for approximating rail rates was developed in conjunction with the study series and is being maintained.

3. Operating characteristics at the boiler level were projected for each fossil-fired power plant in the United States and placed in a data base for future use.

RECOMMENDATIONS

The analysis was conducted under the assumption that abatement gypsum is interchangeable with crude gypsum for use in wallboard and cement. Both advantages and disadvantages are likely. Tests under plant conditions, particularly in cement manufacture, need to be conducted to quantify cost associated with the use of abatement gypsum. Further work to quantify the supply price of crude gypsum of producing areas is needed. The use of estimated average costs for all regions detracts from the accuracy of results but probably does not affect the conclusions. In that regard, gypsum industry cost information is not generally available; it is difficult for a researcher outside the industry to develop the intimate knowledge of the industry required for in-depth analysis. Opportunities to involve industries impacted by abatement products to improve market data bases need to be pursued.

The study suggests that production of abatement gypsum as a waste material would be inexpensive. It is therefore recommended that future research be carried out to assess direct and environmental costs associated with stockpiling abatement gypsum as opposed to ponding limestone sludge. Also, cost estimates need to be developed for producing stockpile-quality gypsum as opposed to wallboard-quality gypsum.

It is felt that gypsum-producing processes would be more advantageous to the industry if they were viewed as a stockpiling alternative as well as a marketing alternative. Information would then be available to utilities to choose ponding sludge, stockpiling gypsum, or meeting quality control necessary for wallboard and cement use in order to market the gypsum. Stockpiled abatement gypsum would be a future source of sulfur.

Locational considerations were shown to play a major role in determining feasibility to produce and market abatement gypsum. This study could only focus on national average mining costs and supply prices. Future work needs to be conducted based on more precise mining costs in specific producing districts. Such work could well include the economic feasibility of new wallboard-producing plants in regions selected for study. Conclusions of this study need to be tested by conducting specific location studies for each plant where gypsum appears to represent a superior economic alternative. For planning future growth in both the utility and gypsum industries, the special situations where production of abatement gypsum has good economic potential should be identified. This will require a cooperative effort between specific companies. The results of this study and any refinements should be used by the cement industry to evaluate potential supply of lower cost raw materials.

In the conduct of this and preceding studies, TVA has developed the basic data and computer methodology to quickly respond to industry requests to evaluate alternative FGD systems and byproduct market opportunities in a variety of ways. This ability needs to be utilized in a continuing program to provide specific plant studies for utilities on their request. Current data bases need to be maintained and upgraded. The cost models should be instrumental in providing information on compliance alternatives. This information would be particularly helpful in planning for new power plants and in evaluating the effect of changing regulations.

REFERENCES

1. U.S. Environmental Protection Agency. Proceedings of Symposium on Flue Gas Desulfurization, Hollywood, Florida, November 1977. Vol. I, EPA-600/7-78-058a (NTIS PB 282 090), Vol. II, EPA-600/7-78-058b (NTIS PB 282 091), March 1978. 434 pp, 1042 pp.

2. Bucy, J. I., R. L. Torstrick, W. L. Anders, J. L. Nevins, and P. A. Corrigan. Potential Abatement Production and Marketing of Byproduct Sulfuric Acid in the U.S. TVA Bull. Y-122; EPA-600/7-78-070, April 1978. 231 pp.

3. Princiotta, F. T. Sulfur Oxide Throwaway Sludge Evaluation Panel (SOTSEP), Vol. I: Final Report - Executive Summary. EPA-650/2-75-010a (NTIS PB 242 618), April 1975. 59 pp.

4. Laseke, Bernard A., Jr. EPA Utility FGD Survey: December 1977 - January 1978. EPA-600/7-78-051a, prepared by PEDCo Environmental, Inc., Cincinnati, Ohio, for U.S. Environmental Protection Agency, Washington, D.C., March 1978 and prior issues.

5. Slack, A. V., and J. M. Potts. Disposal and Use of Byproducts from Flue Gas Desulfurization Processes: Introduction and Overview. In: Proceedings of Symposium on Flue Gas Desulfurization, New Orleans, Louisiana, May 14-17, 1973. EPA-650/2-73-038 (NTIS PB 230 901), December 1973. pp. 747-773.

6. Pearse, G. H. K. Sulphur - Economics and New Uses. Presented at the Canadian Sulfur Symposium, May 30-June 1, 1974. Ottawa, Ontario, Canada.

7. Farmer, M. H., and R. R. Bertrand. Long-Range Sulfur Supply and Demand Model. Final Report. EPA-APTD-1069 (NTIS PB 208 993), November 1971. 422 pp.

8. Allman, P. L. Minerals Yearbook. U.S. Department of Interior, Bureau of Mines, 1968. pp. 559-566.

9. McGlamery, G. G., R. L. Torstrick, W. J. Broadfoot, J. P. Simpson, L. J. Henson, S. V. Tomlinson, and J. F. Young. Detailed Cost Estimates for Advanced Effluent Desulfurization Processes. TVA Bull. Y-90; EPA-600/2-75-006 (NTIS PB 242 541/1WP), January 1975. 418 pp.

10. Waitzman, D. A., J. L. Nevins, and G. A. Slappey. Marketing H2SO4 from SO2 Abatement Sources--The TVA Hypothesis. TVA Bull. Y-71; EPA-650/2-73-051 (NTIS PB 231 671), December 1973. 100 pp.

11. Bucy, J. I., J. L. Nevins, P. A. Corrigan, and A. G. Melicks. Potential Utilization of Controlled SOx Emissions from Power Plants in Eastern United States. In: Proceedings of Symposium on Flue Gas Desulfurization, Vol. II, New Orleans, Louisiana, March 8-11, 1976. EPA-600/2-76-136b (NTIS PB 262 722), May 1976. pp. 647-700.

12. Corrigan, P. A. Preliminary Feasibility Study of Calcium-Sulfur Sludge Utilization in the Wallboard Industry. TVA report S-466, June 21, 1974. 66 pp.

13. Reed, A. H. Gypsum. In: Mineral Facts and Problems, 1975 edition. Bull. 667. U.S. Department of Interior, Bureau of Mines. pp. 469-477.

14. Yeager, L. H. Gypsum-Construction Material Since 3000 B.C. Rock Products, 74(10):113-115, October 1971.

15. Appleyard, F. C. Gypsum and Anhydrite. Industrial Minerals and Rocks. American Institute of Mining, Metallurgical, and Petroleum Engineers, 4th Edition, New York, 1975. pp. 707-723.

16. U.S. Department of Interior, Bureau of Mines. Gypsum Mines and Calcining Plants in the U.S. in 1975. Mineral Industry Surveys, April 15, 1976. 7 pp.

17. Schroder, H. J. Mineral Facts and Problems, 1968 edition. Bull. 650. U.S. Department of Interior, Bureau of Mines. pp. 1037-1048.

18. U.S. Department of Interior, Bureau of Mines. Minerals Yearbook, 1973. p. 7.

19. Ministry of Industry, Trade, and Commerce. Statistics Canada. Catalogue 26-221 Annual, Ottawa, Ontario, Canada, 1974.

20. Reed, A. H. Minerals Yearbook. U.S. Department of Interior, Bureau of Mines, 1973.

21. U.S. District Court, N.D. Wall Products - U.S. National Gypsum Company. Federal Supplement 326. California, 1971. pp. 295-331.

22. U.S. Department of Commerce, Bureau of the Census. Census of Manufacturing - 1947-1972. 1973.

23. Bain, J. S. Economics of Scale, Concentration, and the Condition of Entry in Twenty Manufacturing Industries. American Economic Review, 44:15-39, March 1954.

24. Appleyard, F. C. Construction Materials - Gypsum and Anhydrite. Industrial Minerals and Rocks. American Institute of Mining, Metallurgical, and Petroleum Engineers, 4th Edition, New York, 1975. pp. 185-199.

25. Ando, Jumpei. Status of Flue Gas Desulfurization and Simultaneous Removal of SO_2 and NO_x in Japan. In: Proceedings of Symposium on Flue Gas Desulfurization, Vol. I, New Orleans, Louisiana, March 8-11, 1976. EPA-600/2-76-136a (NTIS PB 252 317), May 1976. pp. 53-78.

26. Lankard, D. R., and W. A. Hedden. Industrial Applications for Process Gypsum. Rock Products, 79(6):72-76, June 1976.

27. Gypsum Association. Gypsum in the Age of Man. 1603 Orringtons Avenue, Evanston, Illinois.

28. Ames, J. A. Construction Materials--Cement and Cement Raw Materials. Industrial Minerals and Rocks. American Institute of Mining, Metallurgical, and Petroleum Engineers, 4th Edition, New York, 1975. pp. 129-155.

29. Brown, B. C. Cement. Mineral Facts and Problems, 1975 edition. Bull. 667. U.S. Department of Interior, Bureau of Mines. 17 pp.

30. U.S. Department of Interior, Bureau of Mines. Statistical Summary of Cement in the United States, 1818-1972. Mineral Industry Surveys, January 1974.

31. U.S. Department of Interior, Bureau of Mines. Cement in 1974. Mineral Industry Surveys, November,1975.

32. Portland Cement Association. U.S. Portland Cement Industry: Plant Information Summary. December 1975.

33. Bower, C. A., and M. Firemen. Seline and Alkali Soils. Soils, the 1957 Yearbook of Agriculture. pp. 282-290.

34. Bureau of Domestic Commerce. Mobile Homes. U.S. Industrial Outlook 1976 with Projections to 1985. pp. 8-12.

35. Beaton, J. D., and S. L. Tisdale. Potential Plant Nutrient Consumption in North America. Bull. 16. The Sulphur Institute, Washington, D.C., July 1969. p. 64.

36. U.S. Department of Interior, Bureau of Mines. Gypsum Mines and Calcining Plants in the United States in 1973. Mineral Industry Surveys, April 1975.

37. Predicasts Terminal Systems, Inc., Cleveland, Ohio, 1975. 71 pp.

38. Stonehouse, D. H. Gypsum and Anhydrite. Canadian Minerals Yearbook - 1974. Ottawa, Ontario, Canada, 1974.

39. Torstrick, R. L., S. V. Tomlinson, and L. J. Henson. Economic Evaluation Techniques, Results, and Computer Modeling for Flue Gas Desulfurization. In: Proceedings of Symposium on Flue Gas Desulfurization, Vol. I, Hollywood, Florida, November 8-11, 1977. EPA-600/7-78-058a (NTIS PB 282 090), March 1978. pp. 118-168.

40. Economic Indicators. Chem. Eng., 84(3):7, January 31, 1977.

41. Borgwardt, R. H. Effect of Forced Oxidation on Limestone-SO_x Scrubber Performance. In: Proceedings of Symposium on Flue Gas Desulfurization, Vol. I, Hollywood, Florida, November 8-11, 1977. EPA-600/7-78-058a (NTIS PB 282 090), March 1978.

APPENDIX A

OTHER GYPSUM-PRODUCING PROCESSES

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APPENDIX A

OTHER GYPSUM-PRODUCING PROCESSES

Except for the MHI (Mitsubishi Heavy Industries) process which removes particulate from the flue gas in a cooler, particulate is removed by ESP upstream from the FGD system. Although Babcock-Hitachi, Kureha, and Mitsui-Chemico are the only processes which specifically mention wastewater treatment, all gypsum-producing processes will require water treatment to remove chlorides and other contaminants if closed-loop operation is to be maintained and wallboard-quality gypsum is to be produced.

BABCOCK-HITACHI LIMESTONE-GYPSUM PROCESS

Hitachi, Ltd., uses a Babcock and Wilcox scrubber to produce by-product gypsum (Figure A-1). The Babcock and Wilcox scrubber is a venturi followed by a perforated plate absorber. The venturi humidifies and cools the gas but does not remove particulate. Efficiencies of 90% are obtainable for removal of SO_2.

Sulfuric acid is used to convert excess limestone ($CaCO_3$) in the recycle stream to gypsum in the reactor and to lower the pH for oxidation. This converted stream is then fed to the oxidizer where air is injected through a JECCO rotary atomizer to oxidize the sulfite to gypsum. The oxidized stream passes to a thickener, a portion is purged for water treatment, and the underflow is centrifuged to yield a cake containing 7-8% moisture.

BORGWARDT EXPERIMENTAL PROCESS

In IERL-RTP studies, Dr. Robert Borgwardt (1) has developed a process to oxidize sulfite slurry to gypsum at low air pressure and stoichiometry. The process (Figure A-2) uses a Penberthy air ejector to oxidize a portion of the scrubber stream. This is carried out either within the scrubber loop or outside the scrubber in a second vessel. Settling and filtration characteristics of the oxidized slurry are reported to be superior when oxidation is conducted within the scrubber loop; however, this mode of operation requires that the scrubber operate at a higher pressure.

1. Borgwardt, R. H. Effect of Forced Oxidation on Limestone-SO_x Scrubber Performance. In: Proceedings of Symposium on Flue Gas Desulfurization, Vol. I, Hollywood, Florida, November 8-11, 1977. EPA-600/7-78-058a, March 1978.

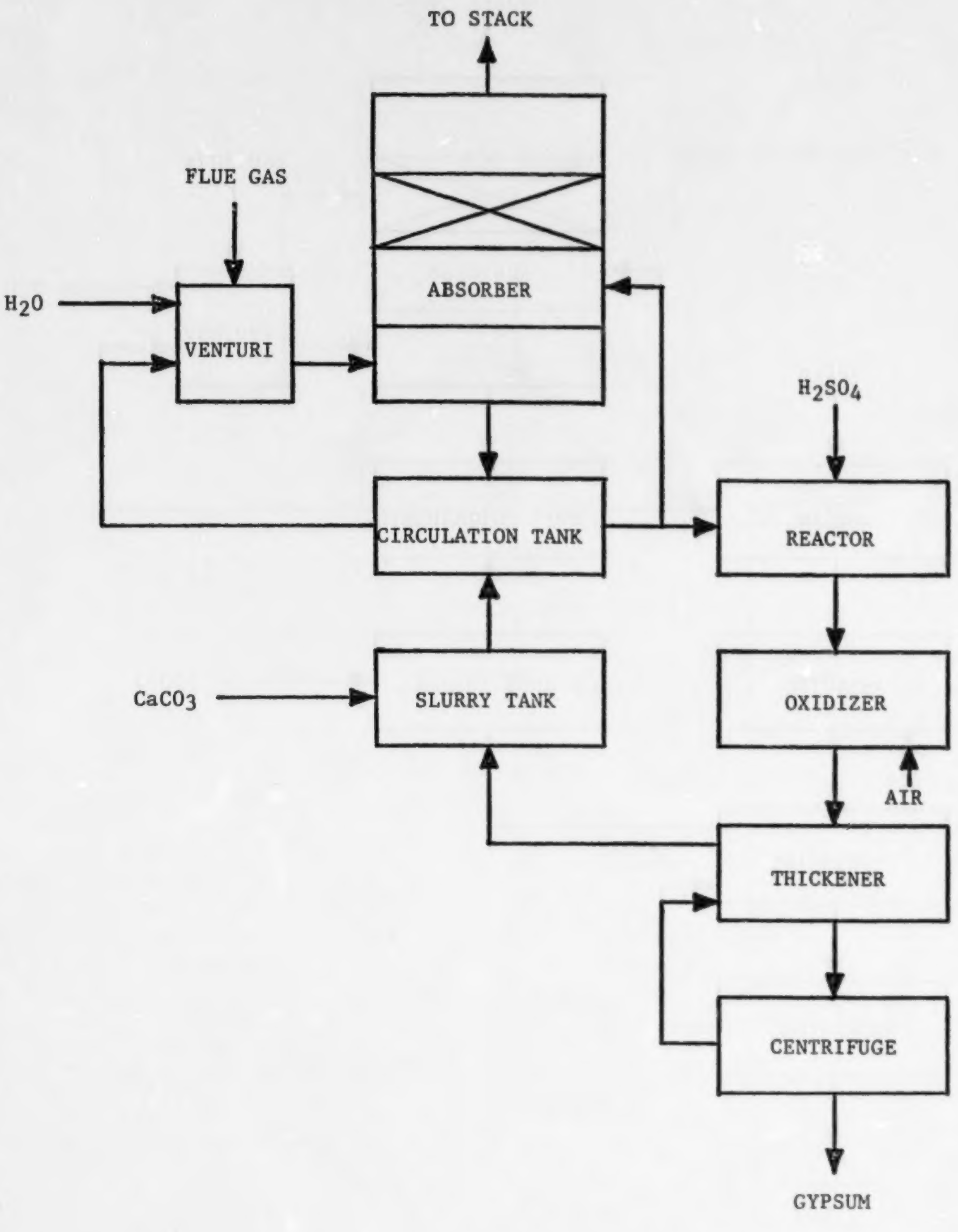
TO STACK
FLUE GAS
H_2O
VENTURI
ABSORBER
H_2SO_4
CIRCULATION TANK
REACTOR
$CaCO_3$
SLURRY TANK
OXIDIZER
AIR
THICKENER
CENTRIFUGE
GYPSUM

Figure A-1. Babcock-Hitachi limestone-gypsum process.

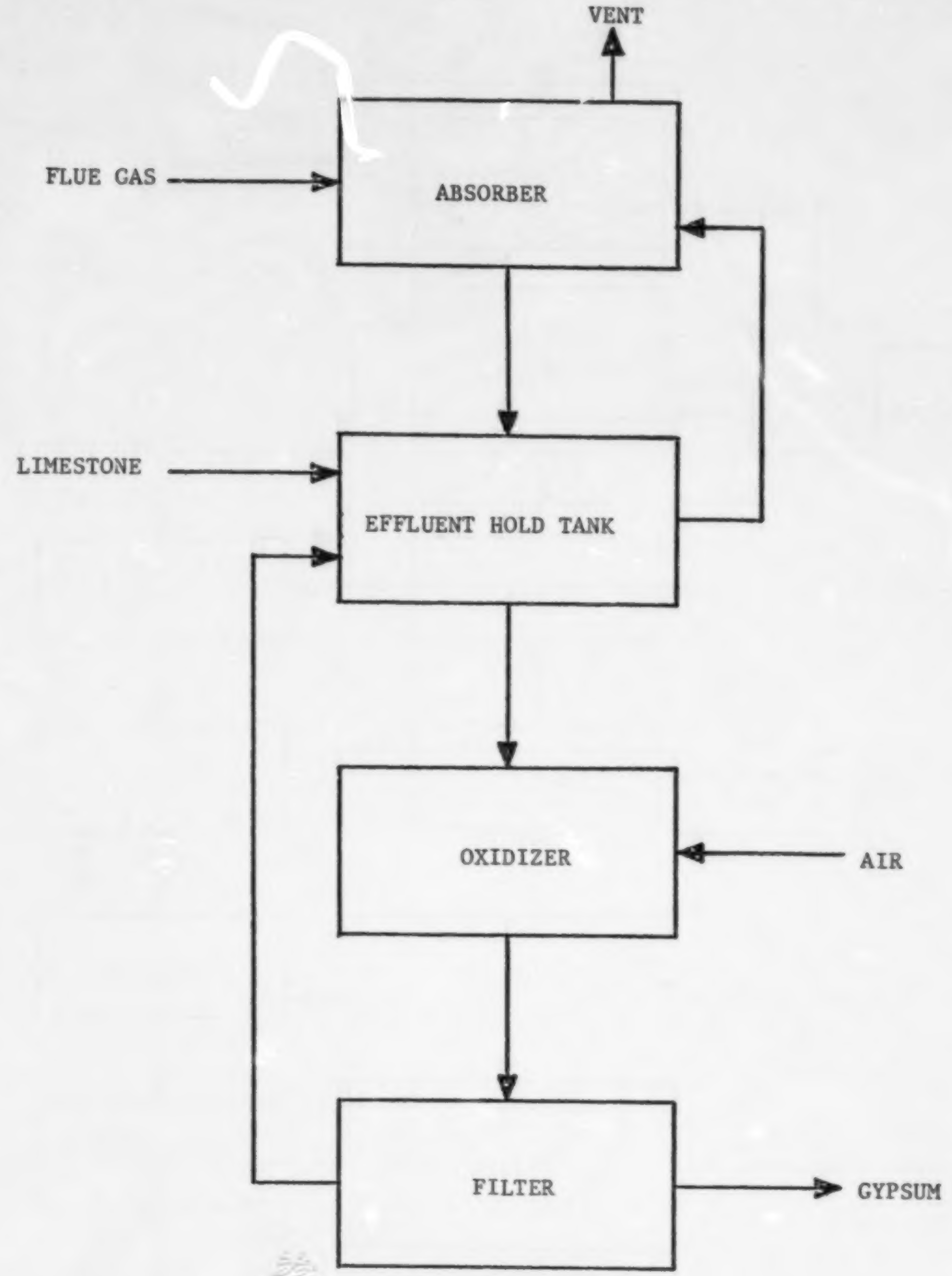
VENT
FLUE GAS
ABSORBER
LIMESTONE
EFFLUENT HOLD TANK
OXIDIZER
AIR
FILTER
GYPSUM

Figure A-2. Borgwardt experimental process.

The process operates at a low air stoichiometry, 3-4, as opposed to other processes which operate at a stoichiometry of 4-6. Oxidation occurs at a typical slurry pH of 5-6, thus eliminating the need for supplemental acid addition. This process has been tested at bench-scale level and in a 10-MW prototype; results indicate that the method is feasible. The quality of the gypsum produced has not been determined. A disadvantage of this process is the partial breakup of gypsum crystals by the ejector.

KASASAKI LIME-MAGNESIUM PROCESS

Kawasaki Heavy Industries has found that the addition of magnesium to a lime-scrubbing process helps to prevent scale formation on process equipment (Figure A-3). Cooled flue gas is contacted with a slurry of calcium and magnesium hydroxides to produce calcium-magnesium sulfite. The resultant slurry is acidified with sulfuric acid and contacted with air. During oxidation the calcium sulfites are converted to gypsum and magnesium sulfites to sulfates. Gypsum is separated from the slurry by a thickener and centrifuge. The magnesium sulfate solution is then reacted with lime to precipitate magnesium hydroxide. Either limestone or lime processes can be used; however, SO_2 removal capabilities are greater with lime scrubbing which can achieve removal efficiencies of greater than 90%. In either case, the gypsum contains about 0.5% magnesium sulfate, but this concentration does not preclude the use of this product for production of cement.

KUREHA SODIUM ACETATE-GYPSUM PROCESS

Kureha Chemical Industry Company, Ltd., has developed a lime desulfurization process (Figure A-4) to remove SO_2 from flue gas as an improvement to their limestone process. The advantages of lime over limestone are numerous. SO_2 removal can be achieved using a smaller absorption tower requiring two stages instead of five. An SO_2 removal efficiency of 99% can be obtained in comparison with limestone which has an efficiency of 90%.

Three reactions are involved in the process to produce wallboard quality gypsum. The SO_2 reacts with sodium acetate to produce sodium sulfite and acetic acid in the absorber. Air is used in the oxidizer to oxidize sodium sulfite to sodium sulfate. This stream is fed to the gypsum recovery reactor where the sodium sulfate reacts with calcium acetate formed from the reaction between lime and acetic acid to produce gypsum and sodium acetate. The sodium acetate is recycled to the absorber. A drum vacuum filter is recommended for separation of the gypsum from the slurry.

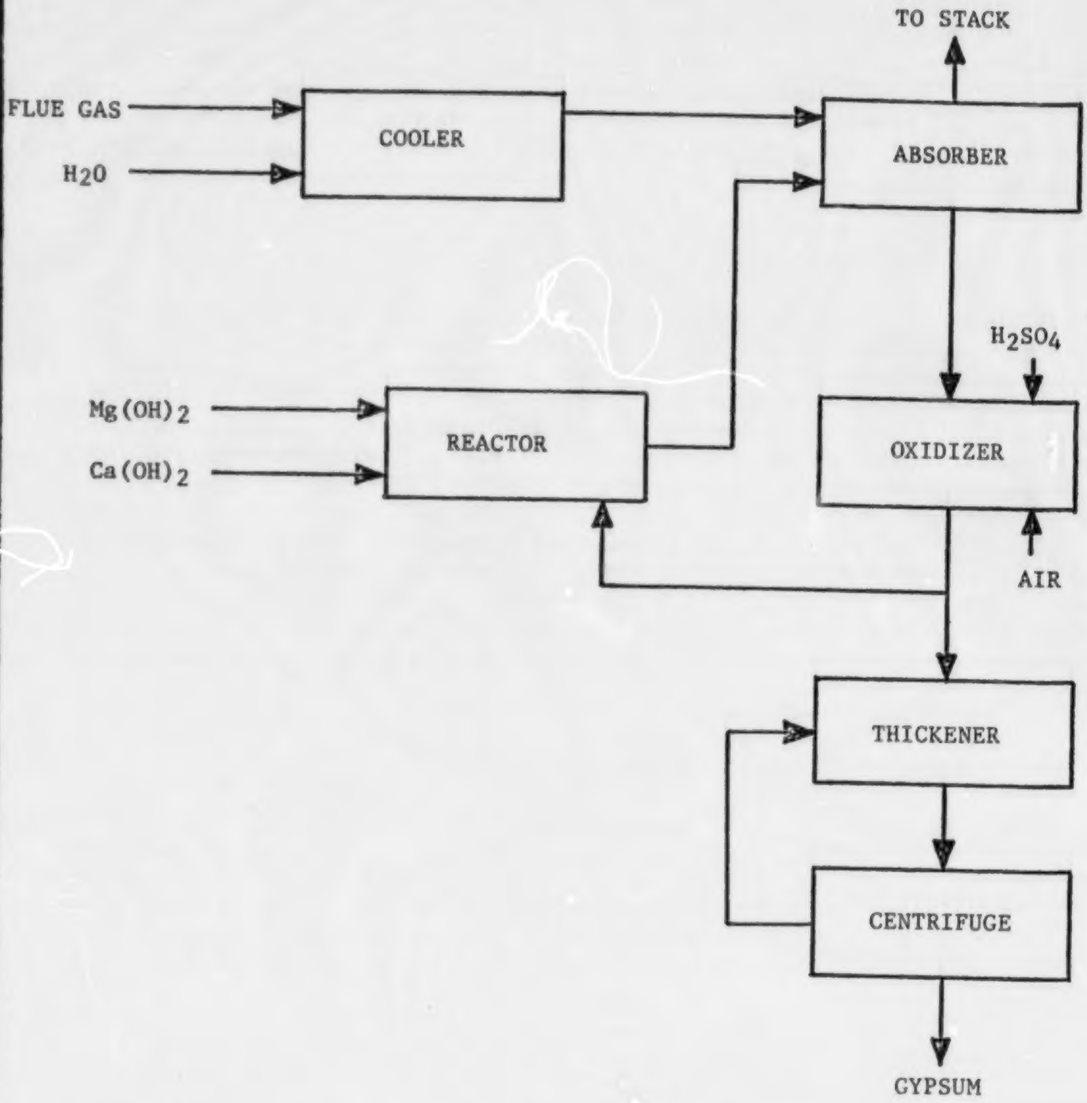
TO STACK
FLUE GAS
COOLER
H2O
ABSORBER
H2SO4
Mg(OH)2
REACTOR
OXIDIZER
Ca(OH)2
AIR
THICKENER
CENTRIFUGE
GYPSUM

Figure A-3. Kawasaki lime-magnesium process.

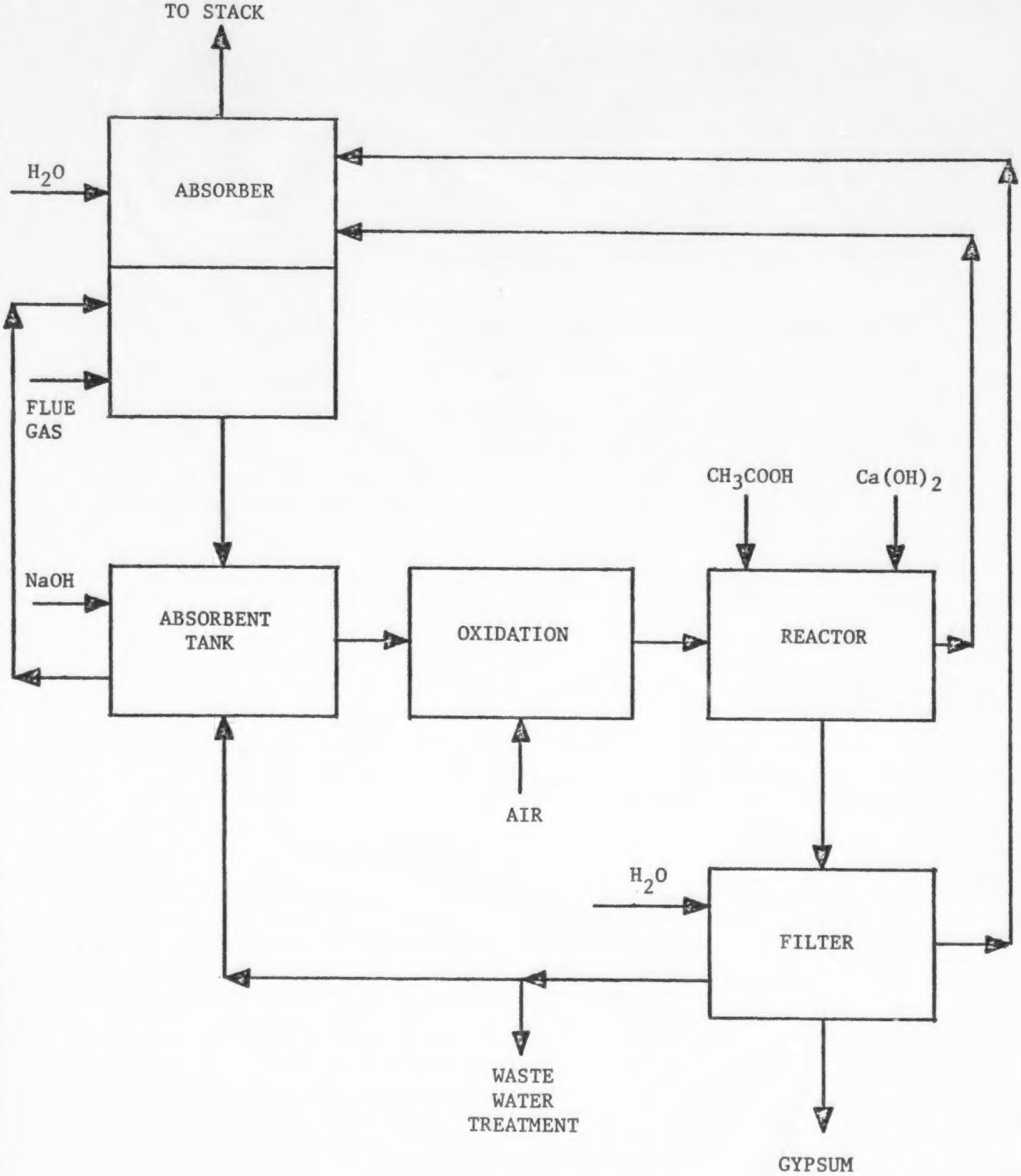
TO STACK
H_2O
ABSORBER
FLUE GAS
NaOH
ABSORBENT TANK
OXIDATION
CH_3COOH
$Ca(OH)_2$
REACTOR
AIR
H_2O
FILTER
WASTE WATER TREATMENT
GYPSUM

Figure A-4. Kureha sodium acetate-gypsum process.

LURGI-SULFACID PROCESS

In the Lurgi-Sulfacid process (Figure A-5), flue gas containing SO_2 is passed over a bed of activated carbon where the SO_2 is converted to sulfuric acid. The acid washed from the activated carbon is neutralized with limestone to produce high-quality gypsum which is suitable for production of wallboard. A centrifuge is used to separate the gypsum produced in the neutralized stream. The advantage of the process is its simplicity. However, it requires the use of rubber-lined absorbers and process equipment and must be designed with upstream fly ash removal to control plugging of the carbon pores with fly ash.

MHI LIME-LIMESTONE PROCESS (MITSUBISHI-JECCO)

Mitsubishi Heavy Industries and JECCO (Japanese Engineering Consulting Company) have developed a process (Figure A-6) for producing gypsum as a byproduct of FGD. The gas is cooled and fly ash is removed in the cooling tower. About 90% of the entering SO_2 is absorbed in the scrubber. Gypsum seed crystals are added to the absorber to provide surface area for reaction to control scaling. The lime slurry bleed from the absorber is adjusted to a pH of 3-4 and oxidized by air under pressure in an oxidation tower. Air is injected into the oxidizer through a JECCO rotary atomizer. Gypsum produced in the oxidizer is dewatered using a basket-type centrifugal filter. The product gypsum cake contains 5-10% moisture.

MITSUI-CHEMICO LIMESTONE-GYPSUM PROCESS

Wallboard-quality gypsum is produced by the Mitsui-Chemico limestone-gypsum process (Figure A-7). Fly ash is removed in an ESP and two venturi scrubbers in series are used to absorb the SO_2 in the flue gas. Ninety percent removal of SO_2 is attainable. A portion of the recycle stream from the first stage is fed to a pH controller where it is contacted with raw flue gas to lower the pH and complete the reaction of limestone with SO_2. This lower pH stream flows to the second stage of the scrubber and a bleedstream is fed to the oxidizer where air is blown in the bottom to convert the sulfite to gypsum. The lower pH promotes oxidation and eliminates the need for supplemental sulfuric acid. An unidentified catalyst is also used to prevent the formation of a calcium sulfate coating on both calcium sulfite and carbonate molecules. The slurry is fed to a centrifuge where the solid gypsum is separated and the supernate is recycled to the scrubber loop. A small amount of supernate is removed for water treatment. In pilot-plant tests, a solid containing 98.2% gypsum was produced. This product is suitable for the production of wallboard, but now is used as an additive in the production of cement. This process requires a large capital investment.

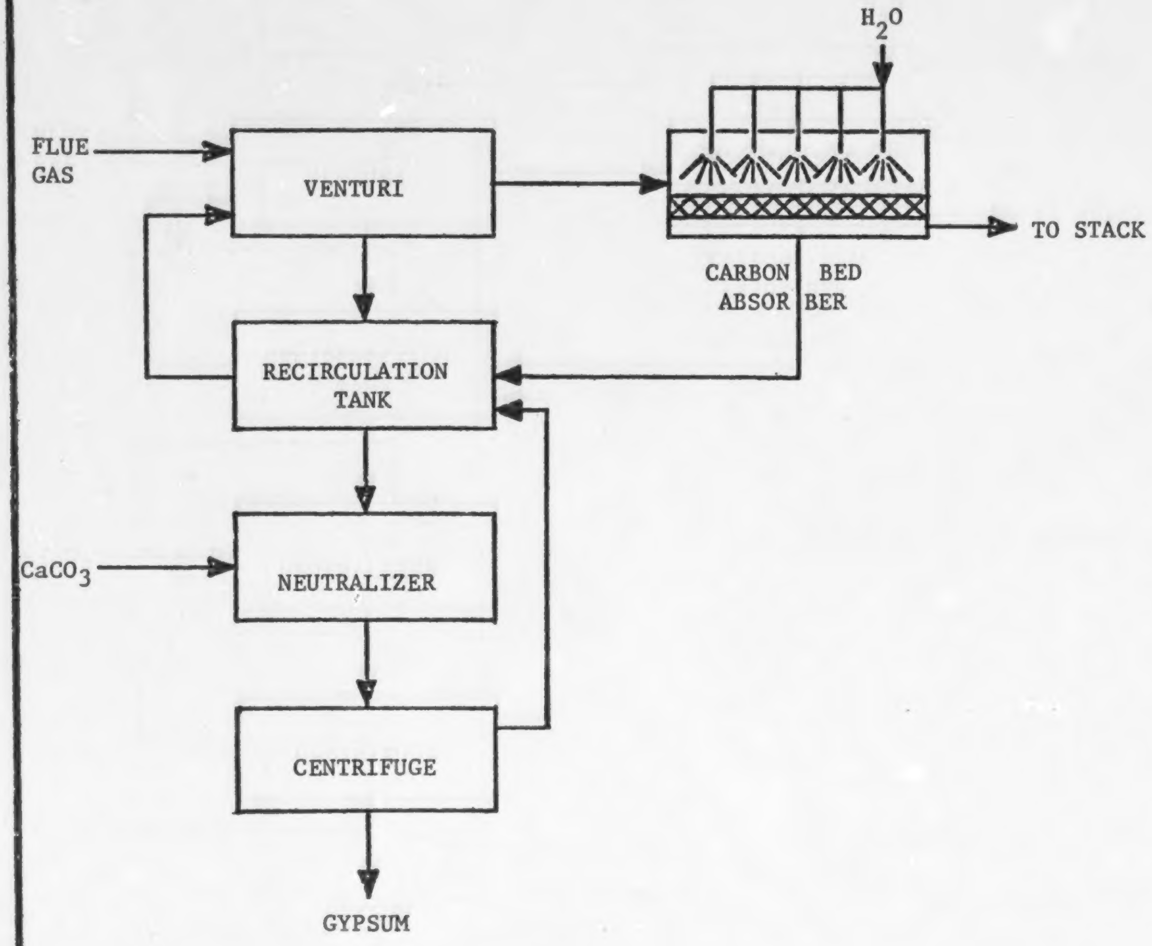
H2O
FLUE GAS
VENTURI
TO STACK
CARBON BED ABSORBER
RECIRCULATION TANK
CaCO3
NEUTRALIZER
CENTRIFUGE
GYPSUM

Figure A-5. Lurgi Sulfacid process.

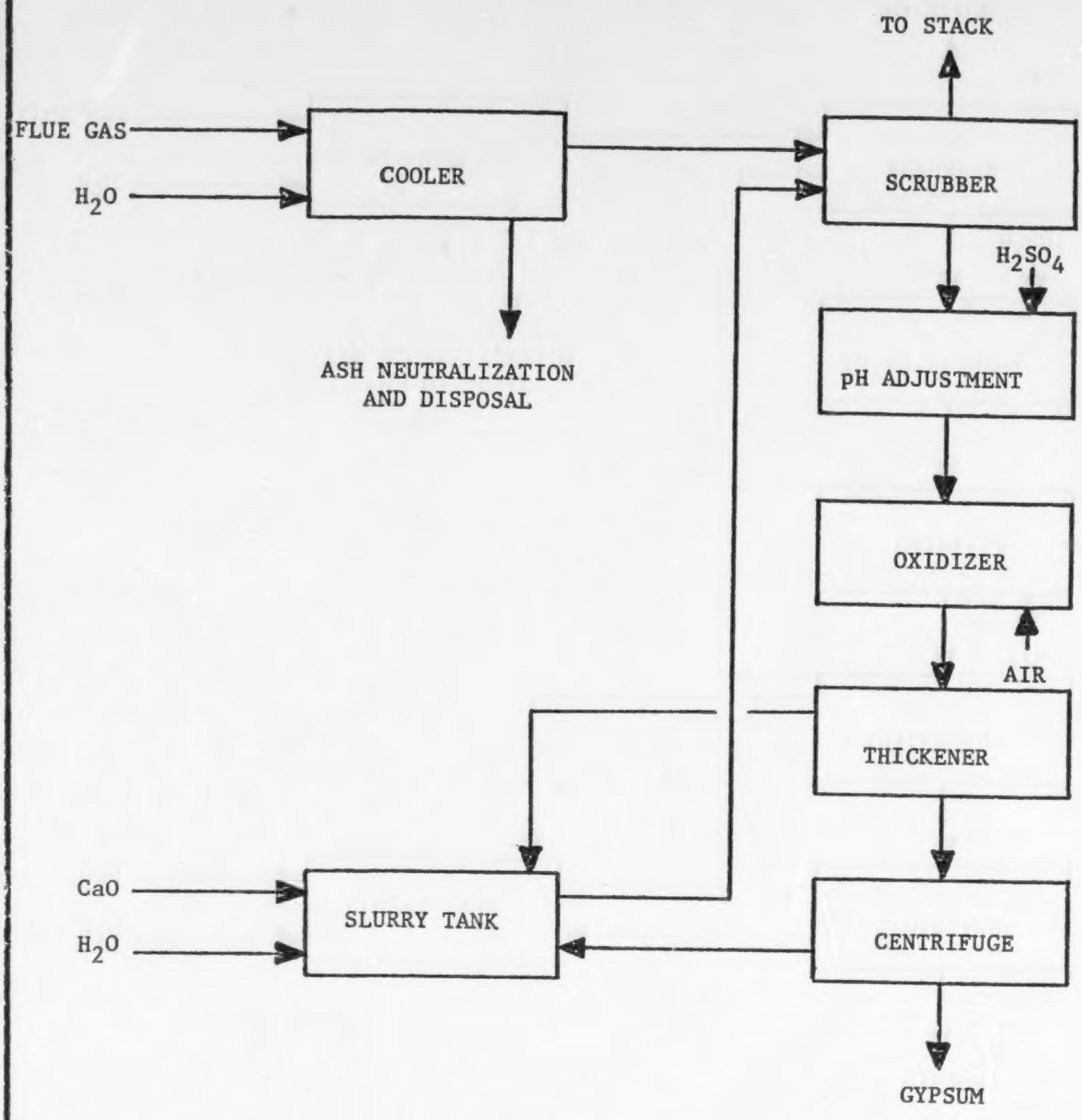
TO STACK
FLUE GAS
H_2O
COOLER
SCRUBBER
H_2SO_4
ASH NEUTRALIZATION AND DISPOSAL
pH ADJUSTMENT
OXIDIZER
AIR
THICKENER
CaO
H_2O
SLURRY TANK
CENTRIFUGE
GYPSUM

Figure A-6. MHI lime-limestone process (Mitsubishi-JECCO).

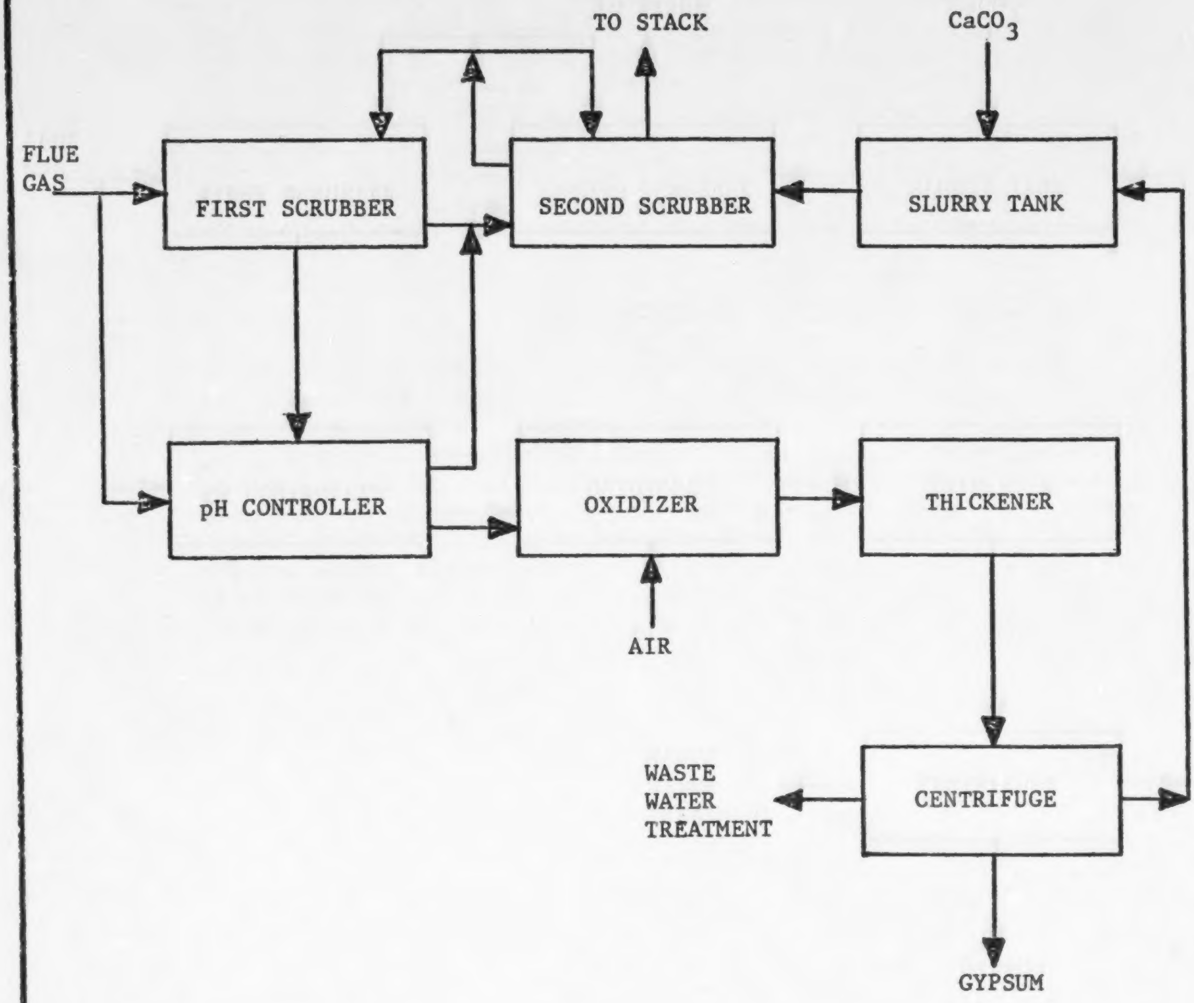
TO STACK
$CaCO_3$
FLUE GAS
FIRST SCRUBBER
SECOND SCRUBBER
SLURRY TANK
pH CONTROLLER
OXIDIZER
THICKENER
AIR
WASTE WATER TREATMENT
CENTRIFUGE
GYPSUM

Figure A-7. Mitsui-Chemico limestone-gypsum process.

MORETANA GYPSUM PROCESS

A joint Fuji Kasui Engineering-Sumitomo Metal Industries process (Figure A-8) produces gypsum using a lime-limestone process. The gas is washed in a prescrubber to saturate and cool the gas stream. A Moretana perforated plate scrubber is used for SO_2 removal. The scrubber is capable of recovering over 95% of the inlet SO_2 as a calcium sulfite slurry. The pH of the slurry is lowered by acidification with sulfuric acid and the slurry is oxidized with air to produce gypsum. A centrifuge is used for dewatering the product. The scrubber system used in this process is reported to be suitable for removal of NO_x as well as SO_2.

PULLMAN-KELLOGG DESULFURIZATION PROCESS

The Pullman-Kellogg process for removal of SO_2 (Figure A-9) is simple but does not produce gypsum of high purity. The process uses a horizontal, weir-type scrubber and SO_2 removal is promoted by the addition of magnesium in the form of the oxide, carbonate, or hydroxide. A portion of the recycle slurry is fed to the oxidizer where it is contacted with air for oxidation to gypsum. The oxidized slurry is thickened and filtered. The resulting solid contains about 15% by weight $CaCO_3$. To be suitable for wallboard production, process modifications would be required to convert a portion of the excess $CaCO_3$ in the slurry to gypsum and lower the pH upstream of the oxidizer. This could be accomplished by the addition of sulfuric acid.

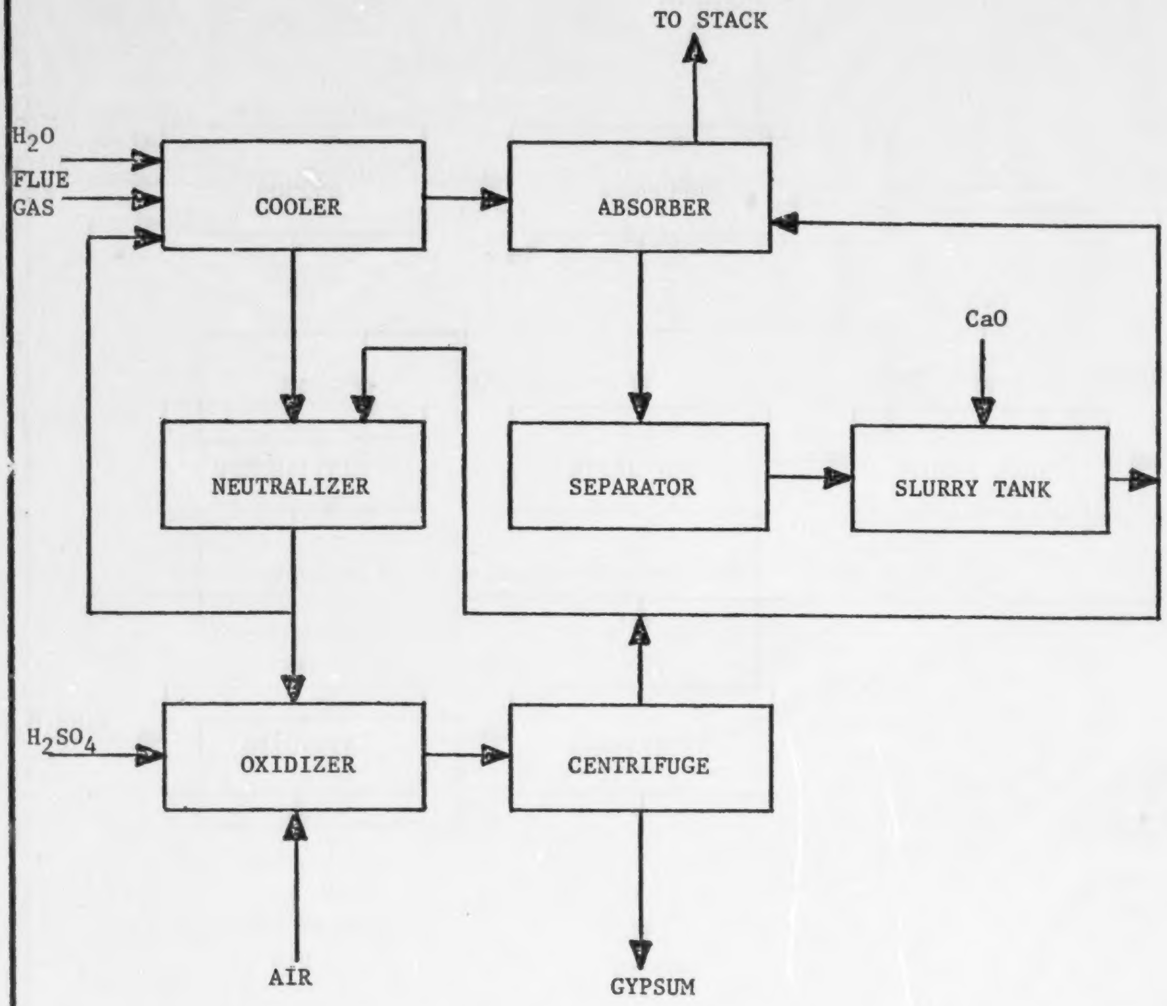
TO STACK
H_2O
FLUE GAS
COOLER
ABSORBER
CaO
NEUTRALIZER
SEPARATOR
SLURRY TANK
H_2SO_4
OXIDIZER
CENTRIFUGE
AIR
GYPSUM

Figure A-8. Moretana gypsum process.

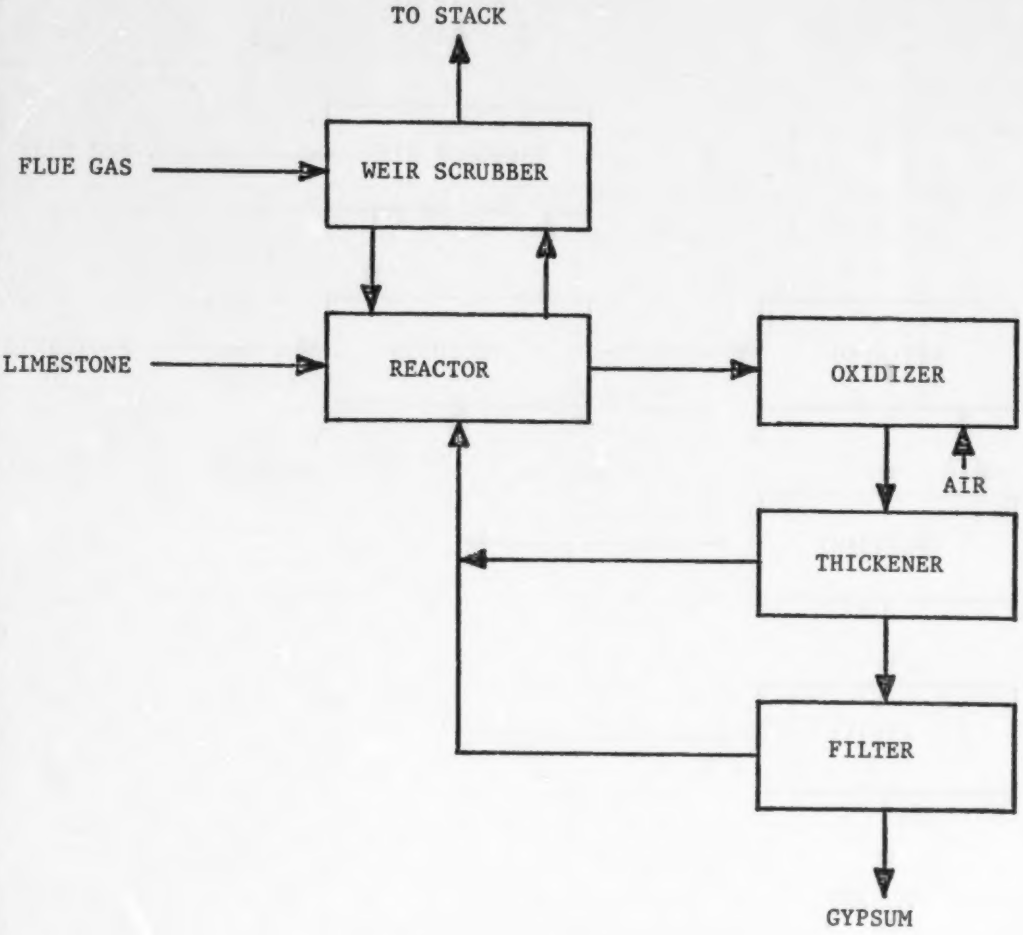
TO STACK
FLUE GAS
WEIR SCRUBBER
LIMESTONE
REACTOR
OXIDIZER
AIR
THICKENER
FILTER
GYPSUM

Figure A-9. Pullman-Kellogg desulfurization process.

APPENDIX B

OPERATING AND INVESTMENT TABULATIONS

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B-14 Limestone-Gypsum Process, 500-MW New Coal-Fired Power Unit, 3.5% Sulfur in Fuel, 90% SO_2 Removal, Regulated Company Economics 188

B-15 Limestone-Gypsum Process, 500-MW New Coal-Fired Power Unit, 3.5% Sulfur in Fuel, 90% SO_2 Removal, Regulated Company Economics 189

TABLE B-1. LIMESTONE SLURRY PROCESS EQUIPMENT LIST AND COST

Area 1--Material Handling

Item	No.	Description	Total material cost, 1977 $
1. Unloading hopper No. 1	1	Capacity 94 ft^3, 8 ft 4 in. side, 2 ft 4 in. bottom, 3 ft deep, carbon steel	2,900
2. Feeder No. 1 (vibrating), limestone	1	210 tons/hr, 42 in. wide x 5 ft long pan, 2-1/2-hp vibrator included	4,800
3. Conveyor (belt) No. 1	1	210 tons/hr, 250 ft/min, 24-in. belt, 10 ft long, 2-1/2-hp motor included	4,300
4. Conveyor (belt) No. 2	1	210 tons/hr, 250 ft/min, 24-in. belt, 172 ft long, 20-hp motor included	23,300
5. Hoppers under pile	3	7 ft 4 in. top, 1 ft 4 in. bottom, 3 ft deep, carbon steel	7,500
6. Feeder No. 2 (vibrating), limestone	3	100 tons/hr, 18 in. wide x 3-1/2 ft long pan, 1-hp vibrator included	7,500
7. Conveyor (belt) No. 3	1	100 tons/hr, 250 ft/min, 18-in. belt, 135 ft long, 3-hp motor included	21,700
8. Pump, tunnel sump	2	5 gpm, 10-ft head, 1/4-hp motor included, carbon steel, neoprene lined	1,800
9. Elevator No. 1	1	100 tons/hr, 16 in. x 8 in. x 8-1/2 in. bucket, 235 ft/min, 15-hp motor included	19,500
10. Bin	1	5,000 ft^3, 3/8 in. carbon steel plate plus structural steel	28,200
11. Car shaker	1	Railroad trackside vibrator	9,700
12. Dust collecting system No. 1	1	2,000 ft^3/min inertial separator XQ cyclone, 2 dust hoppers, fan, and drive	4,300

(continued)

TABLE B-1 (continued)

Item	No.	Description	Total material cost, 1977 $
13. Dust collecting system No. 2	1	6,000 ft3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	8,500
14. Bag filter system	1	14,000 ft3/min automatic fabric dust collectors, bag support, shaker system, isolation damper, external shaker motor and drive, dust hopper, fan and motor for bag filter system (1/2 in feed preparation area)	12,500
Subtotal			156,500

Area 2--Feed Preparation

Item	No.	Description	Total material cost, 1977 $
1. Feeder, bin discharge	2	12-1/2 tons/hr, 10 in. wide x 2-1/2 ft long pan, vibrator included, carbon steel	1,800
2. Feeder, weigh	2	12-1/2 tons/hr, 18-in. belt, 14 ft long, 1-1/2-hp motor included, carbon steel	24,100
3. Crusher, gyratory	2	12-1/2 tons/hr, 0 x 1-1/2 to 3/4 in., 25-hp motor included	33,200
4. Elevator No. 2	2	12-1/2 tons/hr, 235 ft/min, 24 ft ctrs, 6 in. x 4 in. x 4-1/4 in. bucket, 1-hp motor included	7,100
5. Wet ball mill	2	300 tons/day; 8 ft dia x 12 ft long, from 3/4 in. to 200 mesh	317,800
	2	450-hp motors for ball mill	41,800
6. Tank, mills product	1	1,920 gal, 8 ft dia x 5 ft high, vertical with open top, agitator supports, carbon steel	3,700
Lining		Neoprene lining for mill product tank	1,200

(continued)

TABLE B-1 (continued)

	Item	No.	Description	Total material cost, 1977 $
7.	Agitator, mills product tank	1	1 hp, neoprene coated	1,800
8.	Pump, mills product tank	2	96 gpm, 58-ft head, 3-hp motor, centrifugal, with variable-speed drive, carbon steel, neoprene lined	6,500
9.	Tank, slurry feed	1	46,080 gal, 17 ft 4 in. dia. x 27 ft high, vertical with open top, four 1 ft 5 in. wide baffles, agitator supports, carbon steel	5,300
	Lining		1/4 in. neoprene lining	8,300
10.	Agitator, slurry feed tank	1	10 hp, neoprene coated	11,800
11.	Pump, slurry feed tank	2	96 gpm, 58-ft head, 3-hp motor, centrifugal, with variable-speed drive, carbon steel, neoprene lined	6,500
12.	Dust collecting system	1	8,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan and drive	10,500
13.	Hoist	1	5 ton electric	27,900
14.	Bag filter system	1	14,000 ft^3/min automatic fabric dust collectors, bag support, shaker system, isolation damper, external shaker motor and drive, dust hopper, motor and fan for bag filter system (1/2 in materials handling area)	12,500
	Subtotal			521,800

(continued)

TABLE B-1 (continued)

Area 3--SO_2 Scrubbing

	Item	No.	Description	Total material cost, 1977 $
1.	TCA scrubber	4	SO_2 absorber, mobile bed, with demister, 41 ft long x 13 ft wide x 41 ft high, 1/4 in. carbon steel, neoprene lining; 316 SS grids, high density polyethylene spheres, FRP spray headers, chevron vane mist eliminators	2,705,100
2.	Tank, absorber effluent hold	4	240,000 gal, 40 ft dia x 26 ft high, open top, agitator supports, carbon steel	59,200
	Lining		1/4 in. neoprene lining	82,800
3.	Agitator, SO_2 absorber hold tank	4	50 hp, neoprene coated	77,900
4.	Pump, SO_2 absorber recycle slurry	10	11,500 gpm, 105-ft head, 500-hp motor, centrifugal, neoprene lined, belt drive	398,200
5.	Pump, makeup water	2	1,240 gpm, 150-ft head, 100-hp motor, vertical multistage turbine	8,800
6.	Soot blower	40		235,100
	Subtotal			3,567,100

Area 4--Reheat

	Item	No.	Description	Total material cost, 1977 $
1.	Gas reheater	4	Tube type, 2,090 ft^2, one-half of tubes made of Inconel 625 and remaining one-half made of Cor-Ten	491,800
2.	Soot blower	20		117,500
	Subtotal			609,300

(continued)

TABLE B-1 (continued)

Area 5--Gas Handling

Item	No.	Description	Total material cost, 1977 $
1. Fan	4	31 in., 1,200 rpm, 2,500-hp motor included with insulation. (Cost is difference between 31 in. and 15 in. fan. Remainder is allocated to boiler.)	103,500
Subtotal			103,500

Area 6--Solids Disposal

Item	No.	Description	Total material cost, 1977 $
1. Pond feed tank	1	63,000 gal, 21 ft dia x 26 ft high, vertical with open top, carbon steel, 1 ft 8 in. x 26 ft baffles	16,400
Lining		1/4 in. neoprene lining	14,000
2. Agitator	1	7-1/2 hp, neoprene coated	7,900
3. Pump, pond feed tank[a]	4	1,128 gpm, 75-ft head, 50-hp motor, neoprene lined	13,100
4. Pump, recycle pond water[a]	2	1,000 gpm, 150-ft head, 75-hp motor, multistage turbine, cast iron bowl, stainless steel impellers	4,300
Subtotal			55,700

a. Cost for this equipment prorated for fly ash removal.

Area 7--Land

Note: There is no process equipment in this area.

(continued)

TABLE B-1 (continued)

Area 8--Utilities

Note: There is no process equipment in this area.

Area 9--Services

Item	No.	Description	Total material cost, 1977 $
1. Payloader	1	Gasoline type, 2 yd^3	36,400
2. Plant vehicles	-	(allocation)	14,700
3. Maintenance and instrument shop equipment	-	Office, machine tools, and machine shop equipment	38,800
4. Service building equipment	-	Equipment for laboratory, locker room, motor control room, restrooms	51,400
5. Stores equipment	-	Office equipment, shelving, etc.	15,600
Subtotal			156,900

TABLE B-2. LIMESTONE-GYPSUM PROCESS EQUIPMENT LIST AND COST

Area 1--Material Handling

	Item	No.	Description	Total material cost, 1977 $
1.	Unloading hopper No. 1	1	Capacity 94 ft^3, 8 ft 4 in. side, 2 ft 4 in. bottom, 3 ft deep, carbon steel	2,900
2.	Feeder No. 1 (vibrating), limestone	1	210 tons/hr, 42 in. wide x 5 ft long pan, 2-1/2-hp vibrator included	4,800
3.	Conveyor (belt) No. 1	1	210 tons/hr, 250 ft/min, 24-in. belt, 10 ft long, 2-1/2-hp motor included	4,300
4.	Conveyor (belt) No. 2	1	210 tons/hr, 250 ft/min, 24-in. belt, 172 ft long, 20-hp motor included	23,300
5.	Hoppers under pile	3	7 ft 4 in. top, 1 ft 4 in. bottom, 3 ft deep, carbon steel	7,500
6.	Feeder No. 2 (vibrating), limestone	3	100 tons/hr, 18 in. wide x 3-1/2 ft long pan, 1-hp vibrator included	7,500
7.	Conveyor (belt) No. 3	1	100 tons/hr, 250 ft/min, 18-in. belt, 135 ft long, 3-hp motor included	21,700
8.	Pump, tunnel sump	2	5 gpm, 10-ft head, 1/4-hp motor included, carbon steel, neoprene lined	1,800
9.	Elevator No. 1	1	100 tons/hr, 16 in. x 8 in. x 8-1/2 in. bucket, 235 ft/min, 15-hp motor included	19,500
10.	Bin	1	5,000 ft^3, 3/8 in. carbon steel plate plus structural steel	28,200
11.	Car shaker	1	Railroad trackside vibrator	9,700
12.	Dust collecting system No. 1	1	2,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	4,300

(continued)

TABLE B-2 (continued)

Item	No.	Description	Total material cost, 1977 $
13. Dust collecting system No. 2	1	6,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	8,500
14. Bag filter system	1	14,000 ft^3/min automatic fabric dust collectors, bag support, shaker system, isolation damper, external shaker motor and drive, dust hopper, fan and motor for bag filter system (1/2 in feed preparation area)	12,500
Subtotal			156,500

Area 2--Feed Preparation

Item	No.	Description	Total material cost, 1977 $
1. Feeder, bin discharge	2	12-1/2 tons/hr, 10 in. wide x 2-1/2 ft long pan, vibrator included, carbon steel	1,800
2. Feeder, weigh	2	12-1/2 tons/hr, 18-in. belt, 14 ft long, 1-1/2-hp motor included, carbon steel	24,100
3. Crusher, gyratory	2	12-1/2 tons/hr, 0 x 1-1/2 to 3/4 in., 25-hp motor included	33,200
4. Elevator No. 2	2	12-1/2 tons/hr, 235 ft/min, 24 ft ctrs, 6 in. x 4 in. x 4-1/4 in. bucket, 1-hp motor included	7,100
5. Wet ball mill	2	300 tons/day, 8 ft dia x 12 ft long, from 3/4 in. to 200 mesh	317,800
	2	450-hp motors for ball mill	41,800
6. Tank, mills product	1	1,920 gal, 8 ft dia x 5 ft high, vertical with open top, agitator supports, carbon steel	3,700
Lining		Neoprene lining for mill product tank	1,200

(continued)

TABLE B-2 (continued)

Item		No.	Description	Total material cost, 1977 $
7.	Agitator, mills product tank	1	1 hp, neoprene coated	1,800
8.	Pump, mills product tank	2	96 gpm, 58-ft head, 3-hp motor, centrifugal, with variable-speed drive, carbon steel, neoprene lined	6,500
9.	Tank, slurry feed	1	46,080 gal, 17 ft 4 in. dia x 27 ft high, vertical with open top, four 1 ft 5 in. wide baffles, agitator supports, carbon steel	5,300
	Lining		1/4 in. neoprene lining	8,300
10.	Agitator, slurry feed tank	1	10 hp, neoprene coated	11,800
11.	Pump, slurry feed tank	2	96 gpm, 58-ft head, 3-hp motor, centrifugal, with variable-speed drive, carbon steel, neoprene lined	6,500
12.	Dust collecting system	1	8,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	10,500
13.	Hoist	1	5 ton electric	27,900
14.	Bag filter system	1	14,000 ft^3/min automatic fabric dust collectors, bag support, shaker system, isolation damper, external shaker motor and drive, dust hopper, motor and fan for bag filter system (1/2 in materials handling area)	12,500
15.	Tank, acid storage	1	500,000 gal, 50 ft dia x 35 ft high, vertical cylinder, carbon steel	60,800
16.	Pump, acid unload	2	1,200 gpm, 80-ft head, 75-hp motor, carbon steel	10,900
17.	Pump, acid to neutralizer	2	8 gpm, 50-ft head, 1-hp motor, carbon steel	4,200
	Subtotal			597,700

(continued)

TABLE B-2 (continued)

Area 3--SO_2 Scrubbing

	Item	No.	Description	Total material cost, 1977 $
1.	TCA scrubber	4	SO_2 absorber, mobile bed, with demister, 41 ft long x 13 ft wide x 41 ft high, 1/4 in. carbon steel, neoprene lining; 316 SS grids, high density polyethylene spheres, FRP spray headers, chevron vane mist eliminators	2,705,100
2.	Tank, absorber effluent hold	4	240,000 gal, 40 ft dia x 26 ft high, open top, agitator supports, carbon steel	59,200
	Lining		1/4 in. neoprene lining	82,800
3.	Agitator, SO_2 absorber hold tank	4	50 hp, neoprene coated	77,900
4.	Pump, SO_2 absorber recycle slurry	10	11,500 gpm, 105-ft head, 500-hp motor, centrifugal, carbon steel, neoprene lined	398,200
5.	Pump, makeup water	6	130 gpm, 150-ft head, 10-hp motor, vertical multistage turbine	3,800
6.	Soot blower	40		235,100
7.	Pump, bleed	6	179 gpm, 80-ft head, neoprene lined, 7-hp motor	24,400
	Subtotal			3,586,500

Area 4--Reheat

	Item	No.	Description	Total material cost, 1977 $
1.	Gas reheater	4	Tube type, 2,172 ft^2, one-half of tubes made of Inconel 625 and remaining one-half of Cor-Ten	512,200
2.	Soot blower	20		117,500
	Subtotal			629,700

(continued)

TABLE B-2 (continued)

Area 5--Gas Handling

Item	No.	Description	Total material cost, 1977 $
1. Fan	4	31 in., 1,200 rpm, 2,500-hp motor included with insulation. (Cost is difference between 31 in. and 15 in. fan. Remainder is allocated to boiler.)	103,500
Subtotal			103,500

Area 6--Oxidation

Item	No.	Description	Total material cost, 1977 $
1. Tank, neutralization	1	53,000 gal, 19 ft dia x 25 ft high, open top, carbon steel	4,500
Lining		Neoprene lining	8,900
2. Compressor, air, oxidation tower	2	11,500 ft^3/min, outlet 100 psig, 2,500 hp	398,000
3. Tower, oxidation	1	14 ft dia x 50 ft, 5/8 in. carbon steel, neoprene lined, 100 psig	192,000
4. Pump, neutralizer to oxidizer	4	722 gpm (2 in series, each 100-ft head), 40-hp motor, neoprene lined	21,800
5. Pump, oxidizer recycle	4	1,450 gpm (2 in series, each 100-ft head), 100-hp motor, neoprene lined	35,700
Subtotal			660,900

(continued)

TABLE B-2 (continued)

Area 7--Slurry Processing

Item	No.	Description	Total material cost, 1977 $
1. Thickener, gypsum slurry	1	Mechanism for 140 ft dia thickener	111,600
		Tank, concrete, 1,727 yd^3, 140 ft dia x 16 ft 9 in. high, 2 ft thick walls assumed to average sloped bottom, footings, etc.--cost noted below	
2. Filter, belt	2	235 ft^2 effective area, standard accessories	421,100
3. Tank, overflow	1	3,000 gal, 8 ft dia x 8 ft high, open top, carbon steel	4,500
Lining		Neoprene lining	1,200
4. Tank, filter hold	1	3,000 gal, 8 ft dia x 8 ft high, open top, carbon steel	4,500
Lining		Neoprene lining	1,200
5. Tank, wash	4	160 gal, 3 ft x 3 ft, 35 ft^2, open top, carbon steel	900
Lining		Neoprene lining	700
6. Pump, overflow	2	414 gpm, 100-ft head, 20-hp motor, neoprene lined	9,300
7. Pump, underflow	2	322 gpm, 50-ft head, 10-hp motor, neoprene lined	9,300
8. Pump, wash	6	60 gpm, 60-ft head, 1.5-hp motor, neoprene lined	12,500
Subtotal			576,800
		Concrete thickener tank cost is included in concrete foundations	254,700

(continued)

TABLE B-2 (continued)

Area 8--Solids Disposal

Item	No.	Description	Total material cost, 1977 $
1. Conveyor, belt	1	36 tons/hr, 24-in. belt, 700-ft long, 40-hp motor included	80,600
2. Silo, gypsum storage	1	22,800 ft^3, 26 ft dia x 43 ft high, with top and cone bottom, 3/8 in. carbon steel plate	47,300
Subtotal			127,900

Area 9--Land

Note: There is no process equipment in this area.

Area 10--Utilities

Note: There is no process equipment in this area.

Area 11--Services

Item	No.	Description	Total material cost, 1977 $
1. Payloader	1	Gasoline type, 2 yd^3	36,400
2. Plant vehicles	-	(allocation)	14,700
3. Maintenance and instrument shop equipment	-	Office, machine tools, and machine shop equipment	38,800
4. Service building equipment	-	Equipment for laboratory, locker room, motor control room, restrooms	51,400
5. Stores equipment	-	Office equipment, shelving, etc.	15,600
Subtotal			156,900

TABLE B-3. CHIYODA PROCESS EQUIPMENT LIST AND COST

Area 1--Material Handling

Item	No.	Description	Total material cost, 1977 $
1. Unloading hopper No. 1, limestone	1	94 ft^3, 8 ft 4 in. side, 2 ft 4 in. bottom, 3 ft deep, carbon steel	2,900
2. Feeder No. 1 (vibrating), limestone	1	150 tons/hr, 24 in. wide x 42 in. long pan, 2-1/2-hp vibrator included	4,100
3. Conveyor (belt) No. 1	1	150 tons/hr, 250 ft/min, 24-in. belt, 10 ft long, 2-1/2-hp motor included	4,300
4. Conveyor (belt) No. 2	1	150 tons/hr, 250 ft/min, 24-in. belt, 172 ft long, 20-hp motor included	23,300
5. Hoppers under pile	3	7 ft 4 in. top, 1 ft 4 in. bottom, 3 ft deep, carbon steel	7,500
6. Feeder No. 2 (vibrating), limestone	3	70 tons/hr, 18 in. wide x 4 ft long pan, 1-hp vibrator included	7,700
7. Conveyor (belt) No. 3	1	70 tons/hr, 250 ft/min, 18-in. belt, 135 ft long, 3-hp motor included	21,700
8. Pump, tunnel sump	2	5 gpm, 10-ft head, 1/4-hp motor included, carbon steel, neoprene lined	1,800
9. Elevator No. 1	1	70 tons/hr, 16 in. x 8 in. x 12 in. bucket, 235 ft/min, 15-hp motor included	19,500
10. Bin, crusher feed	1	3,600 ft^3, 15 ft x 15 ft x 16 ft, 3/8 in. carbon steel plate plus structural steel	23,100
11. Car shaker	1	Railroad trackside vibrator	9,700

(continued)

TABLE B-3 (continued)

Item	No.	Description	Total material cost, 1977 $
12. Dust collecting system No. 1	1	2,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	4,300
13. Dust collecting system No. 2	1	6,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	8,500
14. Bag filter system	1/2	14,000 ft^3/min automatic fabric dust collectors, bag support, shaker system, isolation damper, external shaker motor and drive, dust hopper, fan and motor for bag filter system (1/2 in feed preparation area)	12,500
15. Bin, $Fe_2(SO_4)_3$ storage	1	2,650 ft^3, 15 ft dia x 15 ft high, with top and cone bottom, carbon steel	4,200
Subtotal			155,100

Area 2--Feed Preparation

Item	No.	Description	Total material cost, 1977 $
1. Vibrator, limestone bin	8		10,300
2. Discharger limestone bin	2	9 tons/hr, 8 in. slide gate, pneumatic, with controls, loading spout with positioner	11,700
3. Feeder, vibrating	2	9 tons/hr, 18 in. wide x 4 ft long pan, 1-hp vibrator included, carbon steel	5,100
4. Feeder, weigh	2	9 tons/hr, 18-in. belt, 14 ft long, 1/2-hp motor included, carbon steel	24,100
5. Crusher, gyratory	2	9 tons/hr, 0 x 1-1/2 in. to 3/4 in., 25-hp motor included	33,200

(continued)

TABLE B-3 (continued)

	Item	No.	Description	Total material cost, 1977 $
6.	Elevator No. 2	2	9 tons/hr, 6 in. x 4 in. x 4-1/4 in. bucket, 235 ft/min, 1-hp motor included	7,100
7.	Wet ball mill	2	214 tons/day, 8 ft dia x 12 ft long, from 3/4 in. to 200 mesh	317,800
		2	450-hp motor	41,800
8.	Tank, mills product	1	1,480 gal, 7 ft dia x 5 ft high, open top, four 6 in. wide baffles, agitator supports, carbon steel	3,600
	Lining		Neoprene lining for mills product tank	1,000
9.	Agitator, mills product tank	1	1 hp, neoprene coated	1,800
10.	Pump, mills product tank	2	74 gpm, 60-ft head, 5-hp motor, centrifugal with variable-speed drive, carbon steel, neoprene lining	11,100
11.	Tank, slurry feed	1	35,500 gal, 16-1/2 ft dia x 24-1/2 ft high, open top, four 16 in. wide baffles, agitator supports, carbon steel	5,400
	Lining		Neoprene lining for slurry feed tank	7,200
12.	Agitator, slurry feed tank	1	10 hp, neoprene coated	11,800
13.	Pump, slurry feed tank	2	74 gpm, 60-ft head, 5-hp motor, centrifugal with variable-speed drive, carbon steel, neoprene lined	11,100
14.	Dust collecting system	1	8,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	10,500
15.	Hoist	1	5 ton electric	27,900

(continued)

TABLE B-3 (continued)

Item	No.	Description	Total material cost, 1977 $
16. Bag filter system	1/2	14,000 ft^3/min (description in material handling area)	12,500
17. Vibrator, $Fe_2(SO_4)_3$ bin	4		5,100
18. Discharger, $Fe_2(SO_4)_3$ bin	1	145 lb/hr, 4 in. nozzle opening	1,600
19. Feeder, vibrating	1	145 lb/hr, 5 in. wide x 18-3/4 in. long pan, 1/2-hp vibrator included	600
20. Feeder, weigh	1	145 lb/hr, 14-in. belt, 3/4-hp motor included	4,600
21. Conveyor, covered screw	1	500 lb/hr, 6 in. dia x 10 ft long, 6-1/2 rpm, 1/3-hp motor	3,300
22. Tank, solution feed	1	846 gal, 5-1/2 ft dia x 5-1/2 ft high, open top, agitator supports, carbon steel	2,100
Lining		Neoprene lining for solution feed tank	600
23. Agitator, solution feed tank		1/2 hp, neoprene coated	1,300
24. Pump, solution feed tank	2	0.5 gpm, 50-ft head, 1/4-hp motor, centrifugal, carbon steel, neoprene lined	3,700
Subtotal			577,900

Area 3--SO_2 Scrubbing

Item	No.	Description	Total material cost, 1977 $
1. Chiyoda absorber-oxidizer	4	SO_2 absorber-oxidizer, 45 ft dia x 15 ft dia x 85 ft high, vertical double shell, 316L SS; polypropylene grid, 3-1/2 in. Tellerette packing, polypropylene mist eliminator	9,730,000

(continued)

TABLE B-3 (continued)

Item	No.	Description	Total material cost, 1977 $
2. Pump, solution to oxidation		Proprietary	
3. Pump, solution to neutralizer	6	1,143 gpm, 150-ft head, 100-hp motor, centrifugal, 316L SS	65,900
4. Compressor, air, oxidation	4	5,000 ft^3/min, 26 psig outlet, with intercooler, 1000-hp motor	508,400
5. Pump, makeup water to absorber	2	440 gpm, 150-ft head, 40-hp motor, vertical multistage turbine, carbon steel	6,200
Subtotal			-

Area 4--Reheat

Item	No.	Description	Total material cost, 1977 $
1. Gas reheater	4	Tube type, 2,106 ft^2, one-half tubes made of Inconel 625 and remaining one-half made of Cor-Ten	499,400
2. Soot blower	20		117,500
Subtotal			616,900

Area 5--Gas Handling

Item	No.	Description	Total material cost, 1977 $
1. Fan	4	32 in., 2,500-hp motor included with insulation. (Cost is difference between 32 in. and 15 in. fan. Remainder is allocated to boiler.)	120,500
Subtotal			120,500

(continued)

TABLE B-3 (continued)

Area 6--Slurry Processing

Item	No.	Description	Total material cost, 1977 $
1. Chiyoda crystallizer	4	365,600 gal, 43 ft dia x 37 ft high, cone bottom, 304L SS, rake mechanism included in price	2,000,000
2. Compressor, crystallizer air sparge	1	4,000 ft^3/min, 15 psig outlet, with intercooler, 900-hp motor	105,800
3. Pump, gypsum slurry	6	99 gpm, 50-ft head, 5-hp motor, centrifugal, carbon steel, neoprene lined	20,300
4. Tank, filter feed	2	6,000 gal, 10 ft dia x 11 ft high, open top, mixer supports, carbon steel	2,800
Lining		Neoprene lining for centrifuge feed tank	4,400
5. Mixer, filter feed tank	2	10 hp, 316L SS	23,400
6. Pump, slurry to filter	3	198 gpm, 50-ft head, 7-hp motor, centrifugal, carbon steel, neoprene lined	9,200
7. Filter, rotary drum vacuum	2	14 ft dia x 14 ft long, including basin and all auxiliaries	366,200
8. Pump, filter to thickener	3	154 gpm, 50-ft head, 5-hp motor, centrifugal, carbon steel, neoprene lined	6,600
9. Thickener, gypsum slurry	1	Mechanism for 110-ft-dia thickener	88,300
		Tank, concrete, 1,012 yd^3, 110 ft dia x 10 ft high, 2-ft-thick walls assumed to average sloped bottom, footings, etc.--cost noted below	

(continued)

TABLE B-3 (continued)

	Item	No.	Description	Total material cost, 1977 $
10.	Pump, thickener overflow	3	2,278 gpm, 50-ft head, 60-hp motor, centrifugal, 316L SS	16,600
11.	Tank, thickener overflow hold	1	45,560 gal, 20-1/2 ft dia x 20-1/2 ft high, open top, carbon steel	6,500
	Lining		Neoprene lining for thickener overflow hold tank	10,100
12.	Pump, absorber liquor return	3	2,278 gpm, 150-ft head, 200-hp motor, centrifugal, 316L SS	43,700
13.	Pump, thickener underflow	2	45 gpm, 150-ft head, 5-hp motor, centrifugal, carbon steel, neoprene lined	6,200
	Subtotal			2,710,100
			Concrete thickener tank cost is included in concrete foundations	118,000

Area 7--Solids Disposal

	Item	No.	Description	Total material cost, 1977 $
1.	Conveyor, belt	1	36 tons/hr, 24-in. belt, 700-ft long, 40-hp motor included, carbon steel	80,600
2.	Silo, gypsum storage	1	22,800 ft^3, 26 ft dia x 43 ft high, with top and cone bottom, 3/8 in. carbon steel plate	47,300
	Subtotal			127,900

TABLE B-4. DOWA PROCESS EQUIPMENT LIST AND COST

Area 1--Material Handling

	Item	No.	Description	Total material cost, 1977 $
1.	Unloading hopper No. 1, limestone	1	94 ft^3, 8 ft 4 in. side, 2 ft 4 in. bottom, 3 ft deep, carbon steel	2,900
2.	Feeder No. 1 (vibrating), limestone	1	150 tons/hr, 24 in. wide x 42 in. long pan, 2-1/2-hp vibrator included	4,100
3.	Conveyor (belt) No. 1	1	150 tons/hr, 250 ft/min, 24-in. belt, 10 ft long, 2-1/2-hp motor included	4,300
4.	Conveyor (belt) No. 2	1	150 tons/hr, 250 ft/min, 24-in. belt, 172 ft long, 20-hp motor included	23,300
5.	Hoppers under pile	3	7 ft 4 in. top, 1 ft 4 in. bottom, 3 ft deep, carbon steel	7,500
6.	Feeder No. 2 (vibrating), limestone	3	70 tons/hr, 18 in. wide x 4 ft long pan, 1-hp vibrator included	7,700
7.	Conveyor (belt) No. 3	1	70 tons/hr, 250 ft/min, 18-in. belt, 135 ft long, 3-hp motor included	21,700
8.	Pump, tunnel sump	2	5 gpm, 10-ft head, 1/4-hp motor included, carbon steel, neoprene lined	1,800
9.	Elevator No. 1	1	70 tons/hr, 16 in. x 8 in. x 12 in. bucket, 235 ft/min, 15-hp motor included	19,500
10.	Bin, crusher feed	1	3,600 ft^3, 15 ft x 15 ft x 16 ft, 3/8 in. carbon steel plate plus structural steel	23,100
11.	Car shaker	1	Railroad trackside vibrator	9,700

(continued)

TABLE B-4 (continued)

Item	No.	Description	Total material cost, 1977 $
12. Dust collecting system No. 1	1	2,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	4,300
13. Dust collecting system No. 2	1	6,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	8,500
14. Bag filter system	1/2	14,000 ft^3/min automatic fabric dust collectors, bag support, shaker system, isolation damper, external shaker motor and drive, dust hopper, fan and motor for bag filter system (1/2 in feed preparation area)	12,500
15. Bin, $Al_2(SO_4)_3$ storage	1	4,580 ft^3, 18 ft dia x 18 ft high, with top and cone bottom, carbon steel	5,800
Subtotal			156,700

Area 2--Feed Preparation

Item	No.	Description	Total material cost, 1977 $
1. Vibrator, limestone bin	8		10,300
2. Discharger, limestone bin	2	9 tons/hr, 8 in. slide gate, pneumatic, with controls, loading spout with positioner	11,700
3. Feeder, vibrating	2	9 tons/hr, 18 in. wide x 4 ft long pan, 1-hp vibrator included, carbon steel	5,100
4. Feeder, weigh	2	9 tons/hr, 18-in. belt, 14 ft long, 1/2-hp motor included, carbon steel	24,100

(continued)

TABLE B-4 (continued)

Item	No.	Description	Total material cost, 1977 $
5. Crusher, gyratory	2	9 tons/hr, 0 x 1-1/2 in. to 3/4 in., 25-hp motor included	33,200
6. Elevator No. 2	2	9 tons/hr, 6 in. x 4 in. x 4-1/4 in. bucket, 235 ft/min, 1-hp motor included	7,100
7. Wet ball mill	2	214 tons/day, 8 ft dia x 12 ft long, from 3/4 in. to 200 mesh	317,800
	2	450-hp motor	41,800
8. Tank, mills product	1	1,400 gal, 7 ft dia x 5 ft high, open top, four 6 in. wide baffles, agitator supports, carbon steel	3,600
Lining		Neoprene lining for mills product tank	1,000
9. Agitator, mills product tank	1	1 hp, neoprene coated	1,800
10. Pump, mills product tank	2	70 gpm, 60-ft head, 3-hp motor, centrifugal with variable-speed drive, carbon steel, neoprene lined	6,500
11. Tank, slurry feed	1	33,600 gal, 15-1/2 ft dia x 25 ft high, open top, four 16 in. wide baffles, agitator supports, carbon steel	4,000
Lining		Neoprene lining for slurry feed tank	5,700
12. Agitator, slurry feed tank	1	10 hp, neoprene coated	11,800
13. Pump, slurry feed tank	2	70 gpm, 60-ft head, 3-hp motor, centrifugal with variable-speed drive, carbon steel, neoprene lined	6,500

(continued)

TABLE B-4 (continued)

	Item	No.	Description	Total material cost, 1977 $
14.	Dust collecting system	1	8,000 ft^3/min inertial separator, XQ cyclone, 2 dust hoppers, fan, and drive	10,500
15.	Hoist	1	5 ton electric	27,900
16.	Bag filter system	1/2	14,000 ft^3/min (description in material handling area)	12,500
17.	Vibrator, $Al_2(SO_4)_3$ bin	4		5,100
18.	Discharge feeder, $Al_2(SO_4)_3$ bin	1	140 lb/hr, 4 in. slide gate, pneumatic, with controls, loading spout with positioner	3,500
19.	Feeder, vibrating	1	560 lb/hr, 18 in. wide x 4 ft long pan, 1-hp vibrator included, carbon steel	2,600
20.	Feeder, weigh	1	560 lb/hr, 18-in. belt, 14 ft long, 1-1/2-hp motor included, carbon steel	12,000
21.	Conveyor, covered screw	1	560 lb/hr, 6 in. dia x 10 ft long, 6-1/2 rpm, 1/3-hp motor	3,300
22.	Tank, solution feed	1	788 gal, 5 ft dia x 6 ft high, open top, agitator supports, carbon steel	2,100
	Lining		Neoprene lining for solution feed tank	600
23.	Agitator, solution feed tank	1	1/2 hp, neoprene coated	1,300
24.	Pump, solution feed tank	2	2 gpm, 50-ft head, 1/4-hp motor, centrifugal, carbon steel, neoprene lined	4,700
	Subtotal			578,100

(continued)

TABLE B-4 (continued)

Area 3--SO_2 Scrubbing

Item	No.	Description	Total material cost, 1977 $
1. TCA scrubber	4	–[a]	2,705,100
2. Tank, absorber effluent hold	4	–[a]	37,800
Lining			51,300
3. Agitator, absorber effluent hold tank	4	–[a]	214,500
4. Pump, solution to oxidation	10	–[a]	484,000
5. Pump, makeup water to absorber	6	–[a]	12,000
Subtotal			3,504,700

a. Description deleted at vendor's request

Area 4--Reheat

Item	No.	Description	Total material cost, 1977 $
1. Gas reheater	4	–[a]	499,400
2. Soot blower	20	–[a]	117,500
Subtotal			616,900

a. Description deleted at vendor's request

Area 5--Gas Handling

Item	No.	Description	Total material cost, 1977 $
1. Fan	4	–[a]	120,500
Subtotal			120,500

a. Description deleted at vendor's request

(continued)

TABLE B-4 (continued)

Area 6--Oxidation

Item	No.	Description	Total material cost, 1977 $
1. Tower, oxidation	4	–[a]	37,300
Lining			50,800
2. Compressor, air oxidation tower	4	–[a]	251,900
Subtotal			340,000

a. Description deleted at vendor's request

Area 7--Slurry Processing

Item	No.	Description	Total material cost, 1977 $
1. Tank, first neutralizing	1	–[a]	9,400
Lining			12,800
2. Agitator, first neutralizing tank	1	–[a]	116,700
3. Pump, No. 1 gypsum slurry	3	–[a]	32,200
4. Tank, second neutralizing	1	–[a]	9,400
Lining			12,800
5. Agitator, second neutralizing tank	1	–[a]	116,700
6. Pump, No. 2 gypsum slurry	3	–[a]	32,200
7. Thickener gypsum slurry	1	–[a]	104,200

(continued)

TABLE B-4 (continued)

Item		No.	Description	Total material cost, 1977 $
8.	Pump, thickener overflow	3	–[a]	20,300
9.	Tank, thickener overflow hold	1	–[a]	7,000
	Lining			2,000
10.	Pump, thickener overflow hold tank	3	–[a]	22,000
11.	Pump, thickener underflow	2	–[a]	10,700
12.	Filter, rotary drum vacuum	2	–[a]	366,200
13.	Soot blower	2	–[a]	3,500
14.	Air receiver	2	–[a]	4,400
15.	Conveyor, filter cake belt	1	–[a]	8,000
	Subtotal			890,500
			Concrete thickener tank cost is included in concrete foundations	100,400

a. Description deleted at vendor's request

Area 8--Purge Unit

Item		No.	Description	Total material cost, 1977 $
1.	Tank, purge	1	–[a]	10,300
	Lining			2,600
2.	Agitator, purge tank	1	–[a]	5,100

(continued)

TABLE B-4 (continued)

Item	No.	Description	Total material cost, 1977 $
3. Tank, settling	1	-[a]	3,900
			30,200
Lining			5,300
4. Pump, settling tank underflow	2	-[a]	3,400
5. Pump, settling tank overflow to disposal	2	-[a]	8,100
Subtotal			68,900

a. Description deleted at vendor's request

Area 9--Solids Disposal

Item	No.	Description	Total material cost, 1977 $
1. Conveyor, belt	1	-[a]	80,600
2. Silo, gypsum storage	1	-[a]	47,300
Subtotal			127,900

a. Description deleted at vendor's request

TABLE B-5. LIMESTONE SLURRY PROCESS - TOTAL CAPITAL INVESTMENT REQUIREMENTS - BASE CASE[a] SUMMARY - PROCESS EQUIPMENT AND INSTALLATION ANALYSIS

(k$)

	Raw materials handling	Feed preparation	SO_2 scrubbing	Reheat	Gas handling	Solids disposal	Land	Utilities	Services	Construction facilities	Total	% of direct investment	% of total capital investment
Direct Costs													
Equipment													
Material	156	522	3,567	609	104	56	-	-	157	-	5,171	28.3	18.1
Labor	38	75	583	103	34	36	-	-	33	-	902	4.9	3.1
Piping and insulation													
Material	2	21	498	14	-	126	-	8	-	-	669	3.7	2.4
Labor	1	36	406	25	-	102	-	16	-	-	586	3.2	2.1
Ductwork, chutes, and supports													
Material	21	9	90	-	768	-	-	-	-	-	888	4.9	3.1
Labor	11	9	92	-	616	-	-	-	-	-	728	4.0	2.6
Concrete foundations													
Material	19	10	35	-	6	2	-	-	-	-	72	0.4	0.3
Labor	106	50	106	-	27	6	-	-	-	-	295	1.6	1.0
Excavation, site preparation, railroads, roads, and pond	-	-	-	-	-	4,449	-	-	469	-	4,918	26.9	17.2
Structural													
Material	16	-	124	-	-	-	-	-	-	-	140	0.8	0.5
Labor	13	-	53	-	-	3	-	-	-	-	69	0.4	0.2
Electrical													
Material	54	85	147	2	190	73	-	14	-	-	365	3.1	2.0
Labor	109	120	146	1	200	240	-	14	-	-	830	4.5	2.9
Instruments													
Material	11	72	238	29	22	16	-	22	-	-	410	2.2	1.4
Labor	5	32	106	13	9	7	-	11	-	-	183	1.0	0.6
Paint and miscellaneous													
Material	2	2	5	-	-	3	-	4	-	-	16	0.1	0.1
Labor	7	8	20	1	1	17	-	4	-	-	58	0.3	0.2
Buildings													
Material	-	95	-	-	-	-	-	-	166	-	261	1.4	0.9
Labor	-	88	-	-	-	-	-	-	52	-	140	0.8	0.5
Land	-	-	-	-	-	-	490	-	-	-	490	2.7	1.7
Construction facilities	-	-	-	-	-	-	-	-	-	870	870	4.8	3.0
Subtotal direct investment	571	1,234	6,216	797	1,977	5,136	490	93	877	870	18,261	100.0	63.9

(continued)

TABLE B-5 (continued)

	Raw materials handling	Feed preparation	SO_2 scrubbing	Reheat	Gas handling	Solids disposal	Land	Utilities	Services	Construction facilities	Total	% of direct investment	% of total capital investment
Indirect Costs													
Engineering design and supervision	51	111	560	72	178	462	44	8	79	78	1,643	9.0	5.7
Construction field expense	63	136	684	88	217	565	54	10	96	96	2,009	11.0	7.0
Contractor fees	29	62	310	40	99	257	25	5	43	43	913	5.0	3.2
Contingency	57	123	621	80	198	514	49	9	88	87	1,826	10.0	6.4
Subtotal fixed investment	771	1,666	8,391	1,077	2,669	6,934	662	125	1,183	1,174	24,652	135.0	86.2
Allowance for startup and modifications	62	133	671	86	213	555	53	10	95	94	1,972	10.8	6.9
Interest during construction	62	133	671	86	213	555	53	10	95	94	1,972	10.8	6.9
Total capital investment	895	1,932	9,733	1,249	3,095	8,044	768	145	1,373	1,362	28,596	156.6	100.0
Total capital investment, %	3.1	6.8	34.0	4.4	10.8	28.1	2.7	0.5	4.8	4.8			

a. Basis

500-MW new coal-fired power unit, 3.5% sulfur in fuel; 90% SO_2 removal; onsite solids disposal.
Stack gas reheat to 175°F by indirect steam reheat.
Disposal pond located 1 mile from power plant.
Midwest plant location represents project beginning mid-1975, ending mid-1978; average cost basis for scaling, mid-1977.
Minimum in-process storage; only pumps are spared.
Investment requirements for removal and disposal of fly ash excluded.
Construction labor shortages with accompanying overtime pay incentive not considered.

TABLE B-6. LIMESTONE-GYPSUM PROCESS - TOTAL CAPITAL INVESTMENT REQUIREMENTS - BASE CASE[a] SUMMARY - PROCESS EQUIPMENT AND INSTALLATION ANALYSIS

(k$)

	Raw materials handling	Feed preparation	SO_2 scrubbing	Reheat	Gas handling	Oxidation	Slurry processing	Solids disposal	Land	Utilities	Services	Construction facilities	Total	% of direct investment	% of total capital investment
Direct Costs															
Equipment															
Material	156	598	3,587	630	104	661	577	127	-	-	157	-	6,597	40.2	25.7
Labor	38	108	590	105	34	346	250	44	-	-	33	-	1,558	9.5	6.1
Piping and insulation															
Material	2	21	501	17	-	46	140	-	-	8	-	-	735	4.5	2.9
Labor	1	36	408	27	-	24	65	-	-	16	-	-	577	3.5	2.2
Ductwork, chutes, and supports															
Material	21	9	90	-	768	21	-	-	-	-	-	-	909	5.5	3.6
Labor	11	9	92	-	616	22	-	-	-	-	-	-	750	4.6	2.9
Concrete foundations															
Material	19	10	35	-	6	14	282	1	-	-	-	-	367	2.2	1.4
Labor	106	51	107	-	27	18	577	4	-	-	-	-	890	5.4	3.5
Excavation, site preparation, railroads, roads, and pond	-	-	-	-	-	-	-	-	-	-	469	-	469	2.9	1.8
Structural															
Material	16	-	124	-	-	5	12	3	-	-	-	-	160	1.0	0.6
Labor	13	-	53	-	-	5	5	8	-	-	-	-	84	0.5	0.3
Electrical															
Material	54	86	148	2	190	51	94	4	-	14	-	-	643	3.9	2.5
Labor	109	121	146	1	200	25	42	10	-	14	-	-	668	4.1	2.6
Instruments															
Material	11	72	238	31	22	9	57	-	-	22	-	-	462	2.8	1.8
Labor	5	32	106	14	9	5	26	-	-	11	-	-	208	1.3	0.8
Paint and miscellaneous															
Material	2	2	5	-	-	3	5	1	-	4	-	-	22	0.1	0.1
Labor	7	8	20	1	1	3	3	1	-	4	-	-	48	0.3	0.2
Buildings															
Material	-	95	-	-	-	-	-	-	-	-	166	-	261	1.6	1.0
Labor	-	88	-	-	-	-	-	-	-	-	52	-	140	0.9	0.6
Land	-	-	-	-	-	-	-	-	63	-	-	-	63	0.4	0.3
Construction facilities	-	-	-	-	-	-	-	-	-	-	-	781	781	4.8	3.0
Subtotal direct investment	571	1,346	6,250	828	1,977	1,258	2,145	203	63	93	877	781	16,392	100.0	63.9

(continued)

TABLE B-6 (continued)

	Raw materials handling	Feed preparation	SO_2 scrubbing	Reheat	Gas handling	Oxidation	Slurry processing	Solids disposal	Land	Utilities	Services	Construction facilities	Total	% of direct investment	% of total capital investment
Indirect Costs															
Engineering design and supervision	51	121	563	75	178	113	193	18	6	8	79	70	1,475	9.0	5.7
Construction field expense	63	148	688	91	217	138	237	22	7	10	96	86	1,803	11.0	7.0
Contractor fees	29	67	314	41	99	63	107	10	3	5	43	39	820	5.0	3.2
Contingency	57	135	625	83	198	126	214	20	6	9	88	78	1,639	10.0	6.4
Subtotal fixed investment	771	1,817	8,440	1,118	2,669	1,698	2,896	273	85	125	1,183	1,054	22,129	135.0	86.2
Allowance for startup and modifications	62	145	675	89	213	136	232	22	7	10	95	84	1,770	10.8	6.9
Interest during construction	62	145	675	89	213	136	232	22	7	10	95	84	1,770	10.8	6.9
Total capital investment	895	2,107	9,790	1,296	3,095	1,970	3,360	317	99	145	1,373	1,222	25,669	156.6	100.0
Total capital investment, %	3.5	8.2	38.1	5.0	12.1	7.7	13.1	1.2	0.4	0.6	5.3	4.8			

a. Basis
500-MW new coal-fired power unit, 3.5% sulfur in fuel; 90% SO_2 removal; onsite solids disposal.
Stack gas reheat to 175°F by indirect steam reheat.
Midwest plant location represents project beginning mid-1975, ending mid-1978; average cost basis for scaling, mid-1977.
Minimum in-process storage; only pumps are spared.
Investment requirements for removal and disposal of fly ash excluded.
Construction labor shortages with accompanying overtime pay incentive not considered.

TABLE B-7. CHIYODA THOROUGHBRED 101 FGD PROCESS - TOTAL CAPITAL INVESTMENT REQUIREMENTS - BASE CASE[a] SUMMARY - PROCESS EQUIPMENT AND INSTALLATION ANALYSIS

(k$)

	Materials handling	Feed preparation	SO_2 absorption-oxidation	Reheat	Gas handling	Slurry processing	Solids disposal	Land	Utilities	Services	Construction facilities	Total	% of direct investment	% of total capital investment
Direct Costs														
Equipment														
Material	155	578	-[b]	617	120	2,710	128	-	-	-	-			
Labor	62	112	-[b]	105	34	150	44	-	-	-	-			
Piping and insulation	3	66	-[b]	46	-	429	-	-	-	-	-			
Ductwork, chutes, and supports	-	-	-[b]	-	1,659	-	-	-	-	-	-			
Concrete foundations	156	71	-[b]	-	31	476	5	-	-	-	-			
Excavation, site preparation, railroads, roads, and ponds	-	-	-	-	-	-	-	-	-	-	-			
Structural	34	-	-[b]	-	-	29	10	-	-	-	-			
Electrical	200	237	-[b]	3	201	286	14	-	-	-	-			
Instruments	20	117	-[b]	47	25	143	-	-	-	-	-			
Paint and miscellaneous	10	11	-[b]	1	1	14	2	-	-	-	-			
Buildings	-	209	-	-	-	-	-	-	-	-	-	209	0.8	0.5
Land	-	-	-	-	-	-	-	63	-	-	-	63	0.2	0.1
Utilities	-	-	-	-	-	-	-	-	117	-	-	117	0.4	0.3
Services	-	-	-	-	-	-	-	-	-	1,168	-	1,168	4.5	2.9
Construction facilities	-	-	-	-	-	-	-	-	-	-	1,234	1,234	4.8	3.0
Subtotal direct investment	640	1,401	13,930	819	2,071	4,237	203	63	117	1,168	1,234	25,883	100.0	63.9

(continued)

TABLE B-7 (continued)

	Materials handling	Feed preparation	SO_2 absorption-oxidation	Reheat	Gas handling	Slurry processing	Solids disposal	Land	Utilities	Services	Construction facilities	Total	% of direct investment	% of total capital investment
Indirect Costs														
Engineering design and supervision												2,329	9.0	5.7
Construction field expense												2,847	11.0	7.0
Contractor fees												1,294	5.0	3.2
Contingency												2,588	10.0	6.4
Subtotal fixed investment												34,941	135.0	86.2
Allowance for startup and modification												2,795	10.8	6.9
Interest during construction												2,795	10.8	6.9
Total capital investment												40,531	156.6	100.0

a. Basis
500-MW new coal-fired power unit, 3.5% sulfur in fuel; 90% SO_2 removal.
Stack gas reheat to 175°F by indirect steam reheat.
Midwest plant location represents project beginning mid-1975, ending mid-1978; average cost basis for scaling, mid-1977.
Minimum in-process storage; only pumps are spared.
Investment requirements for removal and disposal of fly ash excluded.
Construction labor shortages with accompanying overtime pay incentive not considered.

b. Proprietary information.

TABLE B-8. DOWA BASIC ALUMINUM SULFATE-GYPSUM PROCESS - TOTAL CAPITAL INVESTMENT REQUIREMENTS - BASE CASE[a] SUMMARY - PROCESS EQUIPMENT AND INSTALLATION ANALYSIS

(k$)

	Materials handling	Feed preparation	SO_2 absorption	Reheat	Gas handling	Oxidation	Slurry processing	Purge unit	Solids disposal	Land	Utilities	Services	Construction facilities	Total	% of direct investment	% of total capital investment
Direct Costs																
Equipment																
Material	157	578	3,505	617	120	340	890	70	128	-	-	-	-	6,405	41.1	26.3
Labor	66	113	440	105	34	209	204	31	44	-	-	-	-	1,246	8.0	5.1
Piping and insulation	3	66	776	46	-	83	273	24	-	-	-	-	-	1,271	8.2	5.2
Ductwork, chutes, and supports	-	-	183	-	1,659	43	-	-	-	-	-	-	-	1,885	12.1	7.7
Concrete foundations	161	71	126	-	31	44	411	5	5	-	-	-	-	854	5.5	3.5
Excavation, site preparation, railroads, roads, and ponds	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Structural	36	-	150	-	-	22	22	2	10	-	-	-	-	242	1.6	1.0
Electrical	206	237	251	3	201	83	175	15	14	-	-	-	-	1,185	7.6	4.9
Instruments	20	117	288	47	25	22	109	10	-	-	-	-	-	638	4.1	2.6
Paint and miscellaneous	10	11	21	1	1	6	11	1	2	-	-	-	-	64	0.4	0.3
Buildings	-	209	-	-	-	-	-	-	-	-	-	-	-	209	1.3	0.9
Land	-	-	-	-	-	-	-	-	-	63	-	-	-	63	0.4	0.2
Utilities	-	-	-	-	-	-	-	-	-	-	70	-	-	70	0.4	0.3
Services	-	-	-	-	-	-	-	-	-	-	-	703	-	703	4.5	2.9
Construction facilities	-	-	-	-	-	-	-	-	-	-	-	-	742	742	4.8	3.0
Subtotal direct investment	659	1,402	5,740	819	2,071	852	2,095	158	203	63	70	703	742	15,577	100.0	63.9

(continued)

TABLE B-8 (continued)

	Materials handling	Feed preparation	SO_2 absorption	Reheat	Gas handling	Oxidation	Slurry processing	Purge unit	Solids disposal	Land	Utilities	Services	Construction facilities	Total	% of direct investment	% of total capital investment
Indirect Costs																
Engineering design and supervision														1,402	9.0	5.7
Construction field expense														1,714	11.0	7.0
Contractor fees														779	5.0	3.2
Contingency														1,558	10.0	6.4
Subtotal fixed investment														21,030	135.0	86.2
Allowance for startup and modification														1,682	10.8	6.9
Interest during construction														1,682	10.8	6.9
Total capital investment														24,394	156.6	100.0

a. Basis
500-MW new coal-fired power unit, 3.5% sulfur in fuel; 90% SO_2 removal.
Stack gas reheat to 175°F by indirect steam reheat.
Midwest plant location represents project beginning mid-1975, ending mid-1978; average cost basis for scaling, mid-1977.
Minimum in-process storage; only pumps are spared.
Investment requirements for removal and disposal of fly ash excluded.
Construction labor shortages with accompanying overtime pay incentive not considered.

TABLE B-9. LIMESTONE SLURRY PROCESS, 500-MW NEW COAL-FIRED POWER UNIT, 3.5% S IN FUEL, 90% SO_2 REMOVAL, REGULATED COMPANY ECONOMICS

FIXED INVESTMENT: $ 28596000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER UNIT HEAT REQUIREMENT, MILLION BTU /YEAR	POWER UNIT FUEL CONSUMPTION, TONS COAL /YEAR	SULFUR REMOVED BY POLLUTION CONTROL PROCESS, TONS/YEAR	BY-PRODUCT RATE, EQUIVALENT TONS/YEAR WASTE SOLIDS	NET REVENUE, $/TON WASTE SOLIDS	TOTAL OP. COST INCLUDING REGULATED ROI FOR POWER COMPANY, $/YEAR	TOTAL NET SALES REVENUE, $/YEAR	NET ANNUAL INCREASE (DECREASE) IN COST OF POWER, $	CUMULATIVE NET INCREASE (DECREASE) IN COST OF POWER, $
1	7000	31500000	1312500	35400	206000	0.0	13080900	0	13080900	13080900
2	7000	31500000	1312500	35400	206000	0.0	12882600	0	12882600	25963500
3	7000	31500000	1312500	35400	206000	0.0	12684300	0	12684300	38647800
4	7000	31500000	1312500	35400	206000	0.0	12486100	0	12486100	51133900
5	7000	31500000	1312500	35400	206000	0.0	12287800	0	12287800	63421700
6	7000	31500000	1312500	35400	206000	0.0	12089500	0	12089500	75511200
7	7000	31500000	1312500	35400	206000	0.0	11891300	0	11891300	87402500
8	7000	31500000	1312500	35400	206000	0.0	11693000	0	11693000	99095500
9	7000	31500000	1312500	35400	206000	0.0	11494700	0	11494700	110590200
10	7000	31500000	1312500	35400	206000	0.0	11296500	0	11296500	121886700
11	5000	22500000	937500	25600	147200	0.0	9645100	0	9645100	131531800
12	5000	22500000	937500	25600	147200	0.0	9446800	0	9446800	140978600
13	5000	22500000	937500	25600	147200	0.0	9248600	0	9248600	150227200
14	5000	22500000	437500	25600	147200	0.0	9050300	0	9050300	159277500
15	5000	22500000	937500	25600	147200	0.0	8852000	0	8852000	168129500
16	3500	15750000	656200	17400	103000	0.0	7522200	0	7522200	175651700
17	3500	15750000	656200	17400	103000	0.0	7323900	0	7323900	182975600
18	3500	15750000	656200	17400	103000	0.0	7125700	0	7125700	190101300
19	3500	15750000	656200	17400	103000	0.0	6927400	0	6927400	197028700
20	3500	15750000	656200	17400	103000	0.0	6729100	0	6729100	203757800
21	1500	6750000	281200	7700	44100	0.0	4912300	0	4912300	208670100
22	1500	6750000	281200	7700	44100	0.0	4714000	0	4714000	213384100
23	1500	6750000	281200	7700	44100	0.0	4515700	0	4515700	217899800
24	1500	6750000	281200	7700	44100	0.0	4317500	0	4317500	222217300
25	1500	6750000	281200	7700	44100	0.0	4119200	0	4119200	226336500
26	1500	6750000	281200	7700	44100	0.0	3920900	0	3920900	230257400
27	1500	6750000	281200	7700	44100	0.0	3722700	0	3722700	233980100
28	1500	6750000	281200	7700	44100	0.0	3524400	0	3524400	237504500
29	1500	6750000	281200	7700	44100	0.0	3326100	0	3326100	240830600
30	1500	6750000	281200	7700	44100	0.0	3127900	0	3127900	243958500
TOT	127500	573750000	23905500	653500	3752000		243958500	0	243958500	
LIFETIME AVERAGE INCREASE (DECREASE) IN UNIT OPERATING COST										
DOLLARS PER TON OF COAL BURNED							10.21	0.0	10.21	
MILLS PER KILOWATT-HOUR							3.83	0.0	3.83	
CENTS PER MILLION BTU HEAT INPUT							42.52	0.0	42.52	
DOLLARS PER TON OF SULFUR REMOVED							373.31	0.0	373.31	
PROCESS COST DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS							99722200	0	99722200	
LEVELIZED INCREASE (DECREASE) IN UNIT OPERATING COST EQUIVALENT TO DISCOUNTED PROCESS COST OVER LIFE OF POWER UNIT										
DOLLARS PER TON OF COAL BURNED							9.69	0.0	9.69	
MILLS PER KILOWATT-HOUR							3.64	0.0	3.64	
CENTS PER MILLION BTU HEAT INPUT							40.39	0.0	40.39	
DOLLARS PER TON OF SULFUR REMOVED							354.50	0.0	354.50	

TABLE B-10. LIMESTONE-GYPSUM PROCESS, 500-MW NEW COAL-FIRED POWER UNIT,

3.5% S IN FUEL, 90% SO_2 REMOVAL, REGULATED COMPANY ECONOMICS

FIXED INVESTMENT: $ 25670000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER UNIT HEAT REQUIREMENT, MILLION BTU /YEAR	POWER UNIT FUEL CONSUMPTION, TONS COAL /YEAR	SULFUR REMOVED BY POLLUTION CONTROL PROCESS, TONS/YEAR	BY-PRODUCT RATE, EQUIVALENT TONS/YEAR GYPSUM	NET REVENUE, $/TON GYPSUM	TOTAL OP. COST INCLUDING REGULATED ROI FOR POWER COMPANY, $/YEAR	TOTAL NET SALES REVENUE, $/YEAR	NET ANNUAL INCREASE (DECREASE) IN COST OF POWER, $	CUMULATIVE NET INCREASE (DECREASE) IN COST OF POWER, $
1	7000	31500000	1312500	35900	240900	0.0	14769200	0	14769200	14769200
2	7000	31500000	1312500	35900	240900	0.0	14591200	0	14591200	29360400
3	7000	31500000	1312500	35900	240900	0.0	14413200	0	14413200	43773600
4	7000	31500000	1312500	35900	240900	0.0	14235200	0	14235200	58008800
5	7000	31500000	1312500	35900	240900	0.0	14057200	0	14057200	72066000
6	7000	31500000	1312500	35900	240900	0.0	13879200	0	13879200	85945200
7	7000	31500000	1312500	35900	240900	0.0	13701200	0	13701200	99646400
8	7000	31500000	1312500	35900	240900	0.0	13523300	0	13523300	113169700
9	7000	31500000	1312500	35900	240900	0.0	13345300	0	13345300	126515000
10	7000	31500000	1312500	35900	240900	0.0	13167300	0	13167300	139682300
11	5000	22500000	937500	25600	172100	0.0	10835000	0	10835000	150517300
12	5000	22500000	937500	25600	172100	0.0	10657000	0	10657000	161174300
13	5000	22500000	937500	25600	172100	0.0	10479000	0	10479000	171653300
14	5000	22500000	937500	25600	172100	0.0	10301000	0	10301000	181954300
15	5000	22500000	937500	25600	172100	0.0	10123100	0	10123100	192077400
16	3500	15750000	656200	17900	120500	0.0	8289400	0	8289400	200366800
17	3500	15750000	656200	17900	120500	0.0	8111400	0	8111400	208478200
18	3500	15750000	656200	17900	120500	0.0	7933400	0	7933400	216411600
19	3500	15750000	656200	17900	120500	0.0	7755400	0	7755400	224167000
20	3500	15750000	656200	17900	120500	0.0	7577400	0	7577400	231744400
21	1500	6750000	281200	7700	51600	0.0	5086400	0	5086400	236830800
22	1500	6750000	281200	7700	51600	0.0	4908500	0	4908500	241739300
23	1500	6750000	281200	7700	51600	0.0	4730500	0	4730500	246469800
24	1500	6750000	281200	7700	51600	0.0	4552500	0	4552500	251022300
25	1500	6750000	281200	7700	51600	0.0	4374500	0	4374500	255396800
26	1500	6750000	281200	7700	51600	0.0	4196500	0	4196500	259593300
27	1500	6750000	281200	7700	51600	0.0	4018500	0	4018500	263611800
28	1500	6750000	281200	7700	51600	0.0	3840500	0	3840500	267452300
29	1500	6750000	281200	7700	51600	0.0	3662600	0	3662600	271114900
30	1500	6750000	281200	7700	51600	0.0	3484600	0	3484600	274599500
TOT-	127500	573750000	23905500	653500	4388000		274599500	0	274599500	
LIFETIME AVERAGE INCREASE (DECREASE) IN UNIT OPERATING COST										
DOLLARS PER TON OF COAL BURNED							11.49	0.0	11.49	
MILLS PER KILOWATT-HOUR							4.31	0.0	4.31	
CENTS PER MILLION BTU HEAT INPUT							47.86	0.0	47.86	
DOLLARS PER TON OF SULFUR REMOVED							420.20	0.0	420.20	
PROCESS COST DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS							113310500	0	113310500	
LEVELIZED INCREASE (DECREASE) IN UNIT OPERATING COST EQUIVALENT TO DISCOUNTED PROCESS COST OVER LIFE OF POWER UNIT										
DOLLARS PER TON OF COAL BURNED							11.01	0.0	11.01	
MILLS PER KILOWATT-HOUR							4.13	0.0	4.13	
CENTS PER MILLION BTU HEAT INPUT							45.89	0.0	45.89	
DOLLARS PER TON OF SULFUR REMOVED							402.81	0.0	402.81	

RECOMPUTATION BASIS:
0.0% OF NET REVENUE

TABLE B-11. LIMESTONE-GYPSUM PROCESS, 500-MW NEW COAL-FIRED POWER UNIT,

3.5% S IN FUEL, 90% SO_2 REMOVAL, REGULATED COMPANY ECONOMICS

FIXED INVESTMENT: $ 25670000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER UNIT HEAT REQUIREMENT, MILLION BTU /YEAR	POWER UNIT FUEL CONSUMPTION, TONS COAL /YEAR	SULFUR REMOVED BY POLLUTION CONTROL PROCESS, TONS/YEAR	BY-PRODUCT RATE, EQUIVALENT TONS/YEAR GYPSUM	NET REVENUE, $/TON GYPSUM	TOTAL OP. COST INCLUDING REGULATED ROI FOR POWER COMPANY, $/YEAR	TOTAL NET SALES REVENUE, $/YEAR	NET ANNUAL INCREASE (DECREASE) IN COST OF POWER, $	CUMULATIVE NET INCREASE (DECREASE) IN COST OF POWER, $
1	7000	31500000	1312500	35900	240900	2.00	14769200	481800	14287400	14287400
2	7000	31500000	1312500	35900	240900	2.00	14591200	481800	14109400	28396800
3	7000	31500000	1312500	35900	240900	2.00	14413200	481800	13931400	42328200
4	7000	31500000	1312500	35900	240900	2.00	14235200	481800	13753400	56081600
5	7000	31500000	1312500	35900	240900	2.00	14057200	481800	13575400	69657000
6	7000	31500000	1312500	35900	240900	2.00	13879200	481800	13397400	83054400
7	7000	31500000	1312500	35900	240900	2.00	13701200	481800	13219400	96273800
8	7000	31500000	1312500	35900	240900	2.00	13523300	481800	13041500	109315300
9	7000	31500000	1312500	35900	240900	2.00	13345300	481800	12863500	122178800
10	7000	31500000	1312500	35900	240900	2.00	13167300	481800	12685500	134864300
11	5000	22500000	937500	25600	172100	2.00	10835000	344200	10490800	145355100
12	5000	22500000	937500	25600	172100	2.00	10657000	344200	10312800	155667900
13	5000	22500000	437500	25600	172100	2.00	10479000	344200	10134800	165802700
14	5000	22500000	937500	25600	172100	2.00	10301000	344200	9956800	175759500
15	5000	22500000	937500	25600	172100	2.00	10123100	344200	9778900	185538400
16	3500	15750000	656200	17900	120500	2.00	8289400	241000	8048400	193586800
17	3500	15750000	656200	17900	120500	2.00	8111400	241000	7870400	201457200
18	3500	15750000	656200	17900	120500	2.00	7933400	241000	7692400	209149600
19	3500	15750000	656200	17900	120500	2.00	7755400	241000	7514400	216664000
20	3500	15750000	656200	17900	120500	2.00	7577400	241000	7336400	224000400
21	1500	6750000	281200	7700	51600	2.00	5086400	103200	4983200	228983600
22	1500	6750000	281200	7700	51600	2.00	4908500	103200	4805300	233788900
23	1500	6750000	281200	7700	51600	2.00	4730500	103200	4627300	238416200
24	1500	6750000	281200	7700	51600	2.00	4552500	103200	4449300	242865500
25	1500	6750000	281200	7700	51600	2.00	4374500	103200	4271300	247136800
26	1500	6750000	281200	7700	51600	2.00	4196500	103200	4093300	251230100
27	1500	6750000	281200	7700	51600	2.00	4018500	103200	3915300	255145400
28	1500	6750000	281200	7700	51600	2.00	3840500	103200	3737300	258882700
29	1500	6750000	281200	7700	51600	2.00	3662600	103200	3559400	262442100
30	1500	6750000	281200	7700	51600	2.00	3484600	103200	3381400	265823500
TOT	127500	573750000	23905500	653500	4388000		274599500	8776000	265823500	
LIFETIME AVERAGE INCREASE (DECREASE) IN UNIT OPERATING COST										
DOLLARS PER TON OF COAL BURNED							11.49	0.37	11.12	
MILLS PER KILOWATT-HOUR							4.31	0.14	4.17	
CENTS PER MILLION BTU HEAT INPUT							47.86	1.53	46.33	
DOLLARS PER TON OF SULFUR REMOVED							420.20	13.43	406.77	
PROCESS COST DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS							113310500	3776400	109534100	
LEVELIZED INCREASE (DECREASE) IN UNIT OPERATING COST EQUIVALENT TO DISCOUNTED PROCESS COST OVER LIFE OF POWER UNIT										
DOLLARS PER TON OF COAL BURNED							11.01	0.36	10.65	
MILLS PER KILOWATT-HOUR							4.13	0.14	3.99	
CENTS PER MILLION BTU HEAT INPUT							45.89	1.53	44.36	
DOLLARS PER TON OF SULFUR REMOVED							402.81	13.42	389.39	

RECOMPUTATION BASIS:
20.0% OF NET REVENUE

TABLE B-12. LIMESTONE-GYPSUM PROCESS, 500-MW NEW COAL-FIRED POWER UNIT,

3.5% S IN FUEL, 90% SO_2 REMOVAL, REGULATED COMPANY ECONOMICS

FIXED INVESTMENT: $ 25670000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER UNIT HEAT REQUIREMENT, MILLION BTU /YEAR	POWER UNIT FUEL CONSUMPTION, TONS COAL /YEAR	SULFUR REMOVED BY POLLUTION CONTROL PROCESS, TONS/YEAR	BY-PRODUCT RATE, EQUIVALENT TONS/YEAR GYPSUM	NET REVENUE, $/TON GYPSUM	TOTAL OP. COST INCLUDING REGULATED ROI FOR POWER COMPANY, $/YEAR	TOTAL NET SALES REVENUE, $/YEAR	NET ANNUAL INCREASE (DECREASE) IN COST OF POWER, $	CUMULATIVE NET INCREASE (DECREASE) IN COST OF POWER, $
1	7000	31500000	1312500	35900	240900	4.00	14769200	963600	13805600	13805600
2	7000	31500000	1312500	35900	240900	4.00	14591200	963600	13627600	27433200
3	7000	31500000	1312500	35900	240900	4.00	14413200	963600	13449600	40882800
4	7000	31500000	1312500	35900	240900	4.00	14235200	963600	13271600	54154400
5	7000	31500000	1312500	35900	240900	4.00	14057200	963600	13093600	67248000
6	7000	31500000	1312500	35900	240900	4.00	13879200	963600	12915600	80163600
7	7000	31500000	1312500	35900	240900	4.00	13701200	963600	12737600	92901200
8	7000	31500000	1312500	35900	240900	4.00	13523300	963600	12559700	105460900
9	7000	31500000	1312500	35900	240900	4.00	13345300	963600	12381700	117842600
10	7000	31500000	1312500	35900	240900	4.00	13167300	963600	12203700	130046300
11	5000	22500000	937500	25600	172100	4.00	10835000	688400	10146600	140192900
12	5000	22500000	937500	25600	172100	4.00	10657000	688400	9968600	150161500
13	5000	22500000	937500	25600	172100	4.00	10479000	688400	9790600	159952100
14	5000	22500000	937500	25600	172100	4.00	10301000	688400	9612600	169564700
15	5000	22500000	937500	25600	172100	4.00	10123100	688400	9434700	178999400
16	3500	15750000	656200	17900	120500	4.00	8289400	482000	7807400	186806800
17	3500	15750000	656200	17900	120500	4.00	8111400	482000	7629400	194436200
18	3500	15750000	656200	17900	120500	4.00	7933400	482000	7451400	201887600
19	3500	15750000	656200	17900	120500	4.00	7755400	482000	7273400	209161000
20	3500	15750000	656200	17900	120500	4.00	7577400	482000	7095400	216256400
21	1500	6750000	281200	7700	51600	4.00	5086400	206400	4880000	221136400
22	1500	6750000	281200	7700	51600	4.00	4908500	206400	4702100	225838500
23	1500	6750000	281200	7700	51600	4.00	4730500	206400	4524100	230362600
24	1500	6750000	281200	7700	51600	4.00	4552500	206400	4346100	234708700
25	1500	6750000	281200	7700	51600	4.00	4374500	206400	4168100	238876800
26	1500	6750000	281200	7700	51600	4.00	4196500	206400	3990100	242866900
27	1500	6750000	281200	7700	51600	4.00	4018500	206400	3812100	246679000
28	1500	6750000	281200	7700	51600	4.00	3840500	206400	3634100	250313100
29	1500	6750000	281200	7700	51600	4.00	3662600	206400	3456200	253769300
30	1500	6750000	281200	7700	51600	4.00	3484600	206400	3278200	257047500
TOT	127500	573750000	23905500	653500	4388000		274599500	17552000	257047500	
LIFETIME AVERAGE INCREASE (DECREASE) IN UNIT OPERATING COST										
DOLLARS PER TON OF COAL BURNED							11.49	0.74	10.75	
MILLS PER KILOWATT-HOUR							4.31	0.28	4.03	
CENTS PER MILLION BTU HEAT INPUT							47.86	3.06	44.80	
DOLLARS PER TON OF SULFUR REMOVED							420.20	26.86	393.34	
PROCESS COST DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS							113310500	7552900	105757600	
LEVELIZED INCREASE (DECREASE) IN UNIT OPERATING COST EQUIVALENT TO DISCOUNTED PROCESS COST OVER LIFE OF POWER UNIT										
DOLLARS PER TON OF COAL BURNED							11.01	0.73	10.28	
MILLS PER KILOWATT-HOUR							4.13	0.27	3.86	
CENTS PER MILLION BTU HEAT INPUT							45.89	3.06	42.83	
DOLLARS PER TON OF SULFUR REMOVED							402.81	26.85	375.96	

RECOMPUTATION BASIS:
40.0% OF NET REVENUE

TABLE B-13. LIMESTONE-GYPSUM PROCESS, 500-MW NEW COAL-FIRED POWER UNIT,

3.5% S IN FUEL, 90% SO_2 REMOVAL, REGULATED COMPANY ECONOMICS

FIXED INVESTMENT: $ 25670000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER UNIT HEAT REQUIREMENT, MILLION BTU /YEAR	POWER UNIT FUEL CONSUMPTION, TONS COAL /YEAR	SULFUR REMOVED BY POLLUTION CONTROL PROCESS, TONS/YEAR	BY-PRODUCT RATE, EQUIVALENT TONS/YEAR GYPSUM	NET REVENUE, $/TON GYPSUM	TOTAL OP. COST INCLUDING REGULATED ROI FOR POWER COMPANY, $/YEAR	TOTAL NET SALES REVENUE, $/YEAR	NET ANNUAL INCREASE (DECREASE) IN COST OF POWER, $	CUMULATIVE NET INCREASE (DECREASE) IN COST OF POWER, $
1	7000	31500000	1312500	35900	240900	6.00	14769200	1445400	13323800	13323800
2	7000	31500000	1312500	35900	240900	6.00	14591200	1445400	13145800	26469600
3	7000	31500000	1312500	35900	240900	6.00	14413200	1445400	12967800	39437400
4	7000	31500000	1312500	35900	240900	6.00	14235200	1445400	12789800	52227200
5	7000	31500000	1312500	35900	240900	6.00	14057200	1445400	12611800	64839000
6	7000	31500000	1312500	35900	240900	6.00	13879200	1445400	12433800	77272800
7	7000	31500000	1312500	35900	240900	6.00	13701200	1445400	12255800	89528600
8	7000	31500000	1312500	35900	240900	6.00	13523300	1445400	12077900	101606500
9	7000	31500000	1312500	35900	240900	6.00	13345300	1445400	11899900	113506400
10	7000	31500000	1312500	35900	240900	6.00	13167300	1445400	11721900	125228300
11	5000	22500000	937500	25600	172100	6.00	10835000	1032600	9802400	135030700
12	5000	22500000	937500	25600	172100	6.00	10657000	1032600	9624400	144655100
13	5000	22500000	937500	25600	172100	6.00	10479000	1032600	9446400	154101500
14	5000	22500000	937500	25600	172100	6.00	10301000	1032600	9268400	163369900
15	5000	22500000	937500	25600	172100	6.00	10123100	1032600	9090500	172460400
16	3500	15750000	656200	17900	120500	6.00	8289400	723000	7566400	180026800
17	3500	15750000	656200	17900	120500	6.00	8111400	723000	7388400	187415200
18	3500	15750000	656200	17900	120500	6.00	7933400	723000	7210400	194625600
19	3500	15750000	656200	17900	120500	6.00	7755400	723000	7032400	201658000
20	3500	15750000	656200	17900	120500	6.00	7577400	723000	6854400	208512400
21	1500	6750000	281200	7700	51600	6.00	5086400	309600	4776800	213289200
22	1500	6750000	281200	7700	51600	6.00	4908500	309600	4598900	217888100
23	1500	6750000	281200	7700	51600	6.00	4730500	309600	4420900	222309000
24	1500	6750000	281200	7700	51600	6.00	4552500	309600	4242900	226551900
25	1500	6750000	281200	7700	51600	6.00	4374500	309600	4064900	230616800
26	1500	6750000	281200	7700	51600	6.00	4196500	309600	3886900	234503700
27	1500	6750000	281200	7700	51600	6.00	4018500	309600	3708900	238212600
28	1500	6750000	281200	7700	51600	6.00	3840500	309600	3530900	241743500
29	1500	6750000	281200	7700	51600	6.00	3662600	309600	3353000	245096500
30	1500	6750000	281200	7700	51600	6.00	3484600	309600	3175000	248271500
TOT	127500	573750000	23905500	653500	4388000		274599500	26328000	248271500	
LIFETIME AVERAGE INCREASE (DECREASE) IN UNIT OPERATING COST										
DOLLARS PER TON OF COAL BURNED							11.49	1.10	10.39	
MILLS PER KILOWATT-HOUR							4.31	0.42	3.89	
CENTS PER MILLION BTU HEAT INPUT							47.86	4.59	43.27	
DOLLARS PER TON OF SULFUR REMOVED							420.20	40.29	379.91	
PROCESS COST DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS							113310500	11329300	101981200	
LEVELIZED INCREASE (DECREASE) IN UNIT OPERATING COST EQUIVALENT TO DISCOUNTED PROCESS COST OVER LIFE OF POWER UNIT										
DOLLARS PER TON OF COAL BURNED							11.01	1.10	9.91	
MILLS PER KILOWATT-HOUR							4.13	0.41	3.72	
CENTS PER MILLION BTU HEAT INPUT							45.89	4.58	41.31	
DOLLARS PER TON OF SULFUR REMOVED							402.81	40.27	362.54	

RECOMPUTATION BASIS:
60.0% OF NET REVENUE

TABLE B-14. LIMESTONE-GYPSUM PROCESS, 500-MW NEW COAL-FIRED POWER UNIT, 3.5% S IN FUEL, 90% SO_2 REMOVAL, REGULATED COMPANY ECONOMICS

FIXED INVESTMENT: $ 25670000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER UNIT HEAT REQUIREMENT, MILLION BTU /YEAR	POWER UNIT FUEL CONSUMPTION, TONS COAL /YEAR	SULFUR REMOVED BY POLLUTION CONTROL PROCESS, TONS/YEAR	BY-PRODUCT RATE, EQUIVALENT TONS/YEAR GYPSUM	NET REVENUE, $/TON GYPSUM	TOTAL OP. COST INCLUDING REGULATED ROI FOR POWER COMPANY, $/YEAR	TOTAL NET SALES REVENUE, $/YEAR	NET ANNUAL INCREASE (DECREASE) IN COST OF POWER, $	CUMULATIVE NET INCREASE (DECREASE) IN COST OF POWER, $
1	7000	31500000	1312500	35400	240900	8.00	14769200	1927200	12842000	12842000
2	7000	31500000	1312500	35400	240900	8.00	14591200	1927200	12664000	25506000
3	7000	31500000	1312500	35400	240900	8.00	14413200	1927200	12486000	37992000
4	7000	31500000	1312500	35400	240900	8.00	14235200	1927200	12308000	50300000
5	7000	31500000	1312500	35400	240900	8.00	14057200	1927200	12130000	62430000
6	7000	31500000	1312500	35400	240900	8.00	13879200	1927200	11952000	74382000
7	7000	31500000	1312500	35400	240900	8.00	13701200	1927200	11774000	86156000
8	7000	31500000	1312500	35400	240900	8.00	13523300	1927200	11596100	97752100
9	7000	31500000	1312500	35400	240900	8.00	13345300	1927200	11418100	109170200
10	7000	31500000	1312500	35400	240900	8.00	13167300	1927200	11240100	120410300
11	5000	22500000	937500	25600	172100	8.00	10835000	1376800	9458200	129868500
12	5000	22500000	937500	25600	172100	8.00	10657000	1376800	9280200	139148700
13	5000	22500000	937500	25600	172100	8.00	10479000	1376800	9102200	148250900
14	5000	22500000	937500	25600	172100	8.00	10301000	1376800	8924200	157175100
15	5000	22500000	937500	25600	172100	8.00	10123100	1376800	8746300	165921400
16	3500	15750000	656200	17400	120500	8.00	8289400	964000	7325400	173246800
17	3500	15750000	656200	17400	120500	8.00	8111400	964000	7147400	180394200
18	3500	15750000	656200	17400	120500	8.00	7933400	964000	6969400	187363600
19	3500	15750000	656200	17400	120500	8.00	7755400	964000	6791400	194155000
20	3500	15750000	656200	17400	120500	8.00	7577400	964000	6613400	200768400
21	1500	6750000	281200	7700	51600	8.00	5086400	412800	4673600	205442000
22	1500	6750000	281200	7700	51600	8.00	4908500	412800	4495700	209937700
23	1500	6750000	281200	7700	51600	8.00	4730500	412800	4317700	214255400
24	1500	6750000	281200	7700	51600	8.00	4552500	412800	4139700	218395100
25	1500	6750000	281200	7700	51600	8.00	4374500	412800	3961700	222356800
26	1500	6750000	281200	7700	51600	8.00	4196500	412800	3783700	226140500
27	1500	6750000	281200	7700	51600	8.00	4018500	412800	3605700	229746200
28	1500	6750000	281200	7700	51600	8.00	3840500	412800	3427700	233173900
29	1500	6750000	281200	7700	51600	8.00	3662600	412800	3249800	236423700
30	1500	6750000	281200	7700	51600	8.00	3484600	412800	3071800	239495500
TOT	127500	573750000	23905500	653500	4388000		274599500	35104000	239495500	
LIFETIME AVERAGE INCREASE (DECREASE) IN UNIT OPERATING COST										
DOLLARS PER TON OF COAL BURNED							11.49	1.47	10.02	
MILLS PER KILOWATT-HOUR							4.31	0.55	3.76	
CENTS PER MILLION BTU HEAT INPUT							47.86	6.12	41.74	
DOLLARS PER TON OF SULFUR REMOVED							420.20	53.72	366.48	
PROCESS COST DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS							113310500	15105800	98204700	
LEVELIZED INCREASE (DECREASE) IN UNIT OPERATING COST EQUIVALENT TO DISCOUNTED PROCESS COST OVER LIFE OF POWER UNIT										
DOLLARS PER TON OF COAL BURNED							11.01	1.46	9.55	
MILLS PER KILOWATT-HOUR							4.13	0.55	3.58	
CENTS PER MILLION BTU HEAT INPUT							45.89	6.11	39.78	
DOLLARS PER TON OF SULFUR REMOVED							402.81	53.70	349.11	

RECOMPUTATION BASIS:
30.0% OF NET REVENUE

TABLE B-15. LIMESTONE-GYPSUM PROCESS, 500-MW NEW COAL-FIRED POWER UNIT,

3.5% S IN FUEL, 90% SO_2 REMOVAL, REGULATED COMPANY ECONOMICS

FIXED INVESTMENT: $ 25670000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER UNIT HEAT REQUIREMENT, MILLION BTU /YEAR	POWER UNIT FUEL CONSUMPTION, TONS COAL /YEAR	SULFUR REMOVED BY POLLUTION CONTROL PROCESS, TONS/YEAR	BY-PRODUCT RATE, EQUIVALENT TONS/YEAR GYPSUM	NET REVENUE, $/TON GYPSUM	TOTAL OP. COST INCLUDING REGULATED ROI FOR POWER COMPANY, $/YEAR	TOTAL NET SALES, REVENUE, $/YEAR	NET ANNUAL INCREASE (DECREASE) IN COST OF POWER, $	CUMULATIVE NET INCREASE (DECREASE) IN COST OF POWER, $
1	7000	31500000	1312500	35900	240900	10.00	14769200	2409000	12360200	12360200
2	7000	31500000	1312500	35900	240900	10.00	14591200	2409000	12182200	24542400
3	7000	31500000	1312500	35900	240900	10.00	14413200	2409000	12004200	36546600
4	7000	31500000	1312500	35900	240900	10.00	14235200	2409000	11826200	48372800
5	7000	31500000	1312500	35900	240900	10.00	14057200	2409000	11648200	60021000
6	7000	31500000	1312500	35900	240900	10.00	13879200	2409000	11470200	71491200
7	7000	31500000	1312500	35900	240900	10.00	13701200	2409000	11292200	82783400
8	7000	31500000	1312500	35900	240900	10.00	13523300	2409000	11114300	93897700
9	7000	31500000	1312500	35900	240900	10.00	13345300	2409000	10936300	104834000
10	7000	31500000	1312500	35900	240900	10.00	13167300	2409000	10758300	115592300
11	5000	22500000	937500	25600	172100	10.00	10835000	1721000	9114000	124706300
12	5000	22500000	937500	25600	172100	10.00	10657000	1721000	8936000	133642300
13	5000	22500000	937500	25600	172100	10.00	10479000	1721000	8758000	142400300
14	5000	22500000	937500	25600	172100	10.00	10301000	1721000	8580000	150980300
15	5000	22500000	937500	25600	172100	10.00	10123100	1721000	8402100	159382400
16	3500	15750000	656200	17900	120500	10.00	8289400	1205000	7084400	166466800
17	3500	15750000	656200	17900	120500	10.00	8111400	1205000	6906400	173373200
18	3500	15750000	656200	17900	120500	10.00	7933400	1205000	6728400	180101600
19	3500	15750000	656200	17900	120500	10.00	7755400	1205000	6550400	186652000
20	3500	15750000	656200	17900	120500	10.00	7577400	1205000	6372400	193024400
21	1500	6750000	281200	7700	51600	10.00	5086400	516000	4570400	197594800
22	1500	6750000	281200	7700	51600	10.00	4908500	516000	4392500	201987300
23	1500	6750000	281200	7700	51600	10.00	4730500	516000	4214500	206201800
24	1500	6750000	281200	7700	51600	10.00	4552500	516000	4036500	210238300
25	1500	6750000	281200	7700	51600	10.00	4374500	516000	3858500	214096800
26	1500	6750000	281200	7700	51600	10.00	4196500	516000	3680500	217777300
27	1500	6750000	281200	7700	51600	10.00	4018500	516000	3502500	221279800
28	1500	6750000	281200	7700	51600	10.00	3840500	516000	3324500	224604300
29	1500	6750000	281200	7700	51600	10.00	3662600	516000	3146600	227750900
30	1500	6750000	281200	7700	51600	10.00	3484600	516000	2968600	230719500
TOT	127500	573750000	23905500	653500	4388000		274599500	43880000	230719500	
LIFETIME AVERAGE INCREASE (DECREASE) IN UNIT OPERATING COST										
DOLLARS PER TON OF COAL BURNED							11.49	1.84	9.65	
MILLS PER KILOWATT-HOUR							4.31	0.69	3.62	
CENTS PER MILLION BTU HEAT INPUT							47.86	7.65	40.21	
DOLLARS PER TON OF SULFUR REMOVED							420.20	67.15	353.05	
PROCESS COST DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS							113310500	18882200	94428300	
LEVELIZED INCREASE (DECREASE) IN UNIT OPERATING COST EQUIVALENT TO DISCOUNTED PROCESS COST OVER LIFE OF POWER UNIT										
DOLLARS PER TON OF COAL BURNED							11.01	1.83	9.18	
MILLS PER KILOWATT-HOUR							4.13	0.69	3.44	
CENTS PER MILLION BTU HEAT INPUT							45.89	7.64	38.25	
DOLLARS PER TON OF SULFUR REMOVED							402.81	67.12	335.69	

APPENDIX C

CHARACTERISTICS OF THE POWER UTILITY INDUSTRY

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APPENDIX C

CHARACTERISTICS OF THE POWER UTILITY INDUSTRY

In the power industry, either fossil or nuclear fuel is used to generate steam. The steam generated in the boilers is fed to steam turbines which drive generators for producing electricity. Fossil fuel is a general term which refers to either coal, oil, or natural gas. Most coal and oil contain sulfur which during combustion in the boiler is emitted as SO_2 in the stack gas. Natural gas may contain some sulfur, but in relatively small amounts. Nuclear fuels do not contain sulfur and are not consumed in the same manner as fossil fuels; therefore, their use does not result in the emission of SO_2. In presenting characteristics of the power industry below, emphasis is placed on fossil-fired plants which use coal, oil, or natural gas to generate steam.

Detailed information related to the characteristics of the steam-electric utility industry is found in "Steam-Electric Plant Construction Cost and Annual Production Expenses" (FPC-S-250) (1) and "Steam-Electric Plant Air and Water Quality Control Data" (FPC-S-253) (2). Key information given in these publications is included below to characterize the utility industry.

FOSSIL FUELS

During the decade prior to 1967, about 66% of the total annual fossil-fueled power generation was by coal, about 26% by natural gas, and the remaining 8% by residual oil. During the second half of the past decade, when restrictions on the importation of residual oil were removed on the east coast, foreign residual oil began to compete favorably with other fuels. Electric utilities, particularly those near deepwater ports, started to convert from coal to oil and to build new oil-fired units. This process was accelerated with the setting forth of strict sulfur oxide emission control regulations. With the growing shortage in the supply of natural gas, the use of desulfurized or naturally low-sulfur oil offered the most viable solution to the sulfur oxide pollution problem along the entire east coast.

1. Federal Power Commission. Steam-Electric Plant Construction Cost and Annual Production Expenses. Twenty-Sixth Annual Supplement-1973, FPC S-250, April 1975. 185 pp.
2. Federal Power Commission. Steam-Electric Plant Air and Water Quality Control Data, for the year ended December 31, 1973, based on FPC Form 67, FPC S-253, January 1976. 184 pp.

A large proportion of the oil used by electric utilities, particularly along the eastern seaboard, is of foreign origin. In the 1965-72 period, about 398 coal-fired generating units were converted to the use of oil. Economic considerations dictated the conversions initially. More recently, however, the paramount reason for converting to oil has been the requirement to meet strict sulfur emission regulations which the utilities were unable to do using coal. Most of the conversions took place on the east coast at plants with easy access to ocean and river barge transport of lower priced, desulfurized, or naturally low-sulfur imported residual oil. The Arab oil embargo in late 1973 was instrumental in effecting arbitrary and sudden, huge price increases in the world price of oil. In a relatively short period of time, the economic advantage of using imported oil versus coal as a fuel for electric power generation reversed. In early 1974 a number of utilities on the east coast reported 42 oil-burning plants of their systems' capacities as having capability of conversion from oil to coal. A few of these plants have been converted to coal, with conversion by the others contingent upon coal availability. Due to current uncertainties in the long-range oil supply picture and the increasing amounts of nuclear generation becoming available to electric utilities, oil's role in electric generation will probably decline in the future.

Historical Consumption and Characteristics

The historical consumption pattern of coal, natural gas, and oil in the United States from 1969 through 1973 based on FPC Form 67 data is shown in Table C-1. Historical characteristics of coal, oil, and gas for the corresponding period are given in Table C-2. The data indicate that the average heating value of coal, fuel oil, and gas has declined slightly during this period. The data also show a slight decline in the average sulfur content of coal and a significant decline in the average sulfur content of oil. The lower heating values of coal and fuel oil appear to be at the expense of using fuels with lower sulfur contents. The average ash content of coal during the same period increased from about 12.5 to 13.3%.

TABLE C-1. CONSUMPTION PATTERN OF FOSSIL FUELS IN THE UNITED STATES, 1969-73 (1)

	Total Btu (10^{15})				% of total Btu		
Year	Coal	Oil	Gas	Total	Coal	Oil	Gas
1969	7.065	1.577	3.429	12.071	58.5	13.1	28.4
1970	7.098	2.008	3.820	12.926	54.9	15.5	29.6
1971	7.244	2.328	3.841	13.413	54.0	17.4	28.6
1972	7.794	2.816	3.811	14.421	53.9	19.6	26.5
1973	8.583	3.270	3.517	15.370	55.8	21.3	22.9

TABLE C-2. HISTORICAL FOSSIL FUEL CHARACTERISTICS FOR THE PERIOD 1969-73 (1)

	Year				
	1969	1970	1971	1972	1973
Coal					
Average heating value, Btu/lb	11,628	11,276	11,169	11,176	11,090
Average sulfur content, % by wt	2.59	2.58	2.47	2.39	2.32
Equivalent SO_2 content, lb SO_2/MBtu	4.46	4.58	4.42	4.28	4.27
Average ash content, % by wt	12.53	13.72	13.85	13.41	13.29
Fuel Oil					
Average heating value, Btu/gal	148,727	147,991	147,017	146,285	145,772
Average sulfur content, % by wt	1.68	1.52	1.28	1.07	0.98
Equivalent SO_2 content, lb SO_2/MBtu	1.80	1.64	1.40	1.18	1.08
Gas					
Average heating value, Btu/ft^3	1,033	1,031	1,030	1,028	1,028

1. Federal Power Commission. Steam-Electric Plant Air and Water Quality Control Data, for the year ended December 31, 1973, based on FPC Form 67, FPC S-253, January 1976. 184 pp.

Projected 1978 Consumption and Characteristics

In 1973 utilities were also requested by the FPC to project fuel consumption and characteristics for 1978. The majority of utilities provided FPC with these projections. For the utilities which did not project this information, fuel consumption and characteristics were assumed to be the same as that reported for 1973. Based on the updated projections, Table C-3 shows the consumption rates and characteristics of fossil fuels projected to be used during 1978.

A comparison of the total projected 1978 coal, fuel oil, and gas consumption with the historical 1973 fuel consumption by region is shown in Table C-4. Figure C-1 shows the overall trend in fossil fuel consumption from 1969 through 1978. The projections indicate a general increase in the consumption of coal and oil, but a slight decrease in the consumption of gas. The regional increases or decreases are primarily influenced by fuel availability and price. In reviewing the data, it must be remembered that a significant amount of new generating capacity between 1973 and 1978 is from nuclear units. The data shown include the effect of projected decreases in fossil fuel utilization as a result of new nuclear units coming online as well as changes in fossil fuel consumption resulting from decreases in fuel availability or increases in cost.

TABLE C-3. PROJECTED 1978 FOSSIL FUEL CONSUMPTION

RATES AND CHARACTERISTICS

	All plants	Plants out of compliance
Coal		
Total consumption		
ktons	475,570	226,780
10^9 Btu	10,408,290	5,125,075
Heating value, Btu/lb	10,943	11,300
Sulfur content, % by wt	2.12	2.81
Equivalent SO_2 content, lb SO_2/MBtu	3.87	4.97
Oil		
Total consumption		
kbbl	620,247	110,167
10^9 Btu	3,827,427	686,900
Heating value, Btu/gal	146,924	148,454
Sulfur content	0.99	1.42
Equivalent SO_2 content, lb SO_2/MBtu	1.08	1.54
Gas		
Total consumption		
Mft^3	2,556,021	108,239
10^9 Btu	2,602,232	116,968
Heating value, Btu/ft^3	1,018	1,081

TABLE C-4. COMPARISON OF PROJECTED 1978 REGIONAL FOSSIL FUEL CONSUMPTION WITH 1973 CONSUMPTION

Geographic region[a]	Coal, ktons	Oil, kbbl	Gas, Mft^3
Historical 1973 Consumption (1)			
New England	1,078.2	82,930.0	6,070.2
Middle Atlantic	46,993.3	144,692.4	64,728.9
East North Central	135,959.4	23,337.9	105,593.6
West North Central	31,623.2	3,442.9	352,816.6
South Atlantic	75,860.1	141,382.4	202,664.9
East South Central	63,060.9	6,513.8	73,749.3
West South Central	4,733.3	20,847.0	1,957,067.4
Mountain	23,928.4	8,989.3	207,631.7
Pacific	3,741.0	76,965.5	451,217.3
U.S. Total	386,977.8	509,101.2	3,421,519.9
Projected 1978 Consumption[b]			
U.S. Total	475,570	620,247	2,556,021

a. The states included in each geographic region are: New England - CT, ME, MA, NH, RI, VT; Middle Atlantic - NJ, NY, PA; East North Central - IL, IN, MI, OH, WI; West North Central - IA, KS, MN, MO, NE, ND, SD; South Atlantic - DE, DC, FL, GA, MD, NC, SC, VA, WV; East South Central - AL, KY, MS, TN; West South Central - AR, LA, OK, TX; Mountain - AZ, CO, ID, MT, NV, NM, UT, WY; Pacific - CA, OR, WA.

b. Regional consumption data not available.

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1. Federal Power Commission. Steam-Electric Plant Air and Water Quality Control Data, for the year ended December 31, 1973, based on FPC Form 67, FPC S-253, January 1976. 184 pp.

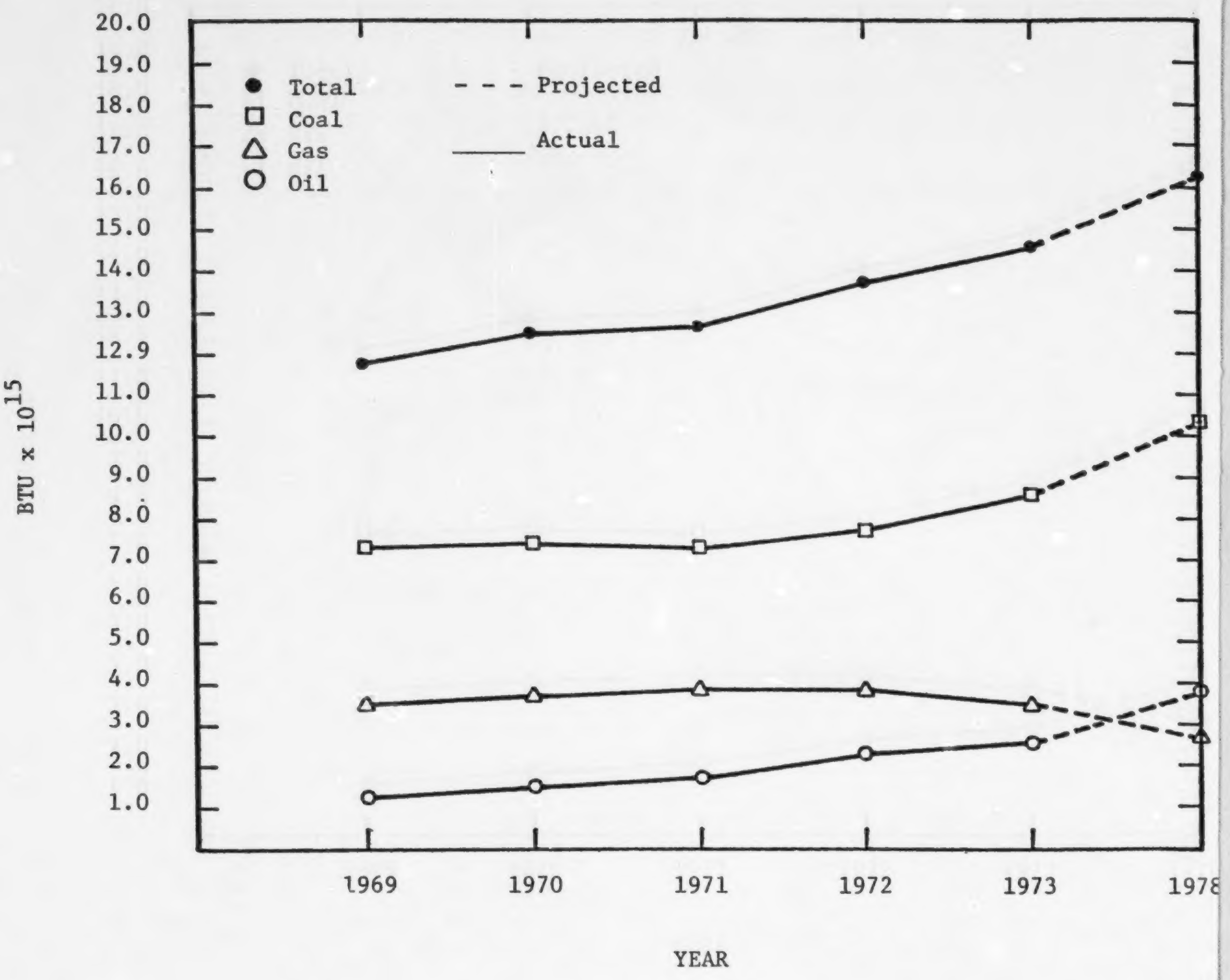

Figure C-1. Trends in the consumption of coal, oil, and gas from 1969-78.

POWER PLANT CHARACTERISTICS

Plant Location

The locations of major coal-, oil-, and gas-fired steam-electric power plants based on 1973 FPC data are shown in Figures C-2 through C-4 respectively. Figure C-5 shows the location of plants which use multiple fuel mixes for the same period. The data show coal-fired plants to be scattered from the east to the west coast. The highest concentration of coal-fired plants is in the Midwest. Oil-fired power plants are most predominant along the east and west coasts and the lower Mississippi Valley; however, they are also found at other scattered locations in the Midwestern States. Gas-fired plants are predominant near the Louisiana and Texas Gulf Coast and adjacent states, but like oil-fired plants, are also found at other locations. At the end of 1973, plants with facilities for using multiple fuels were widely scattered.

Plant Size

Historical data for conventional fossil-fueled steam-electric generating plants for the total power industry are shown in Table C-5. An analysis of these data indicates that total fossil-fueled power generation has generally doubled every 10 years. New plants are constructed to (1) provide additional capacity for the increasing electrical demand and (2) provide replacement capacity for older, less efficient plants which are being retired. The total installed steam-electric generating capacity from fossil-fueled plants increased from 26 kMW in 1938 to over 318 kMW in 1973. During the same period, average plant size in megawatts increased from 22 to 322. The total number of plants varies annually as new plants are built and old plants are retired. At the end of 1973, there were 219 fossil-fueled plants 500 MW or larger.

Most power plants consist of a number of separate units which are capable of producing power independently of the other units within the plant. Each unit generally includes a separate boiler for generating steam, a separate turbine and generator for producing electricity, and separate flue gas handling facilities. Although some plants have common flue gas stacks for multiple boilers, most boilers are designed with separate stacks. Modular units allow for servicing and maintenance without significantly affecting the output of the overall plant and allows for the addition of new generating capacity without interfering with the operation of the existing facilities.

A diagram showing the general layout of a plant, including facilities for SO_2 control, is shown in Figure C-6. This diagram illustrates the relationships between plant, boilers, stacks, and facilities for controlling SO_2 emissions.

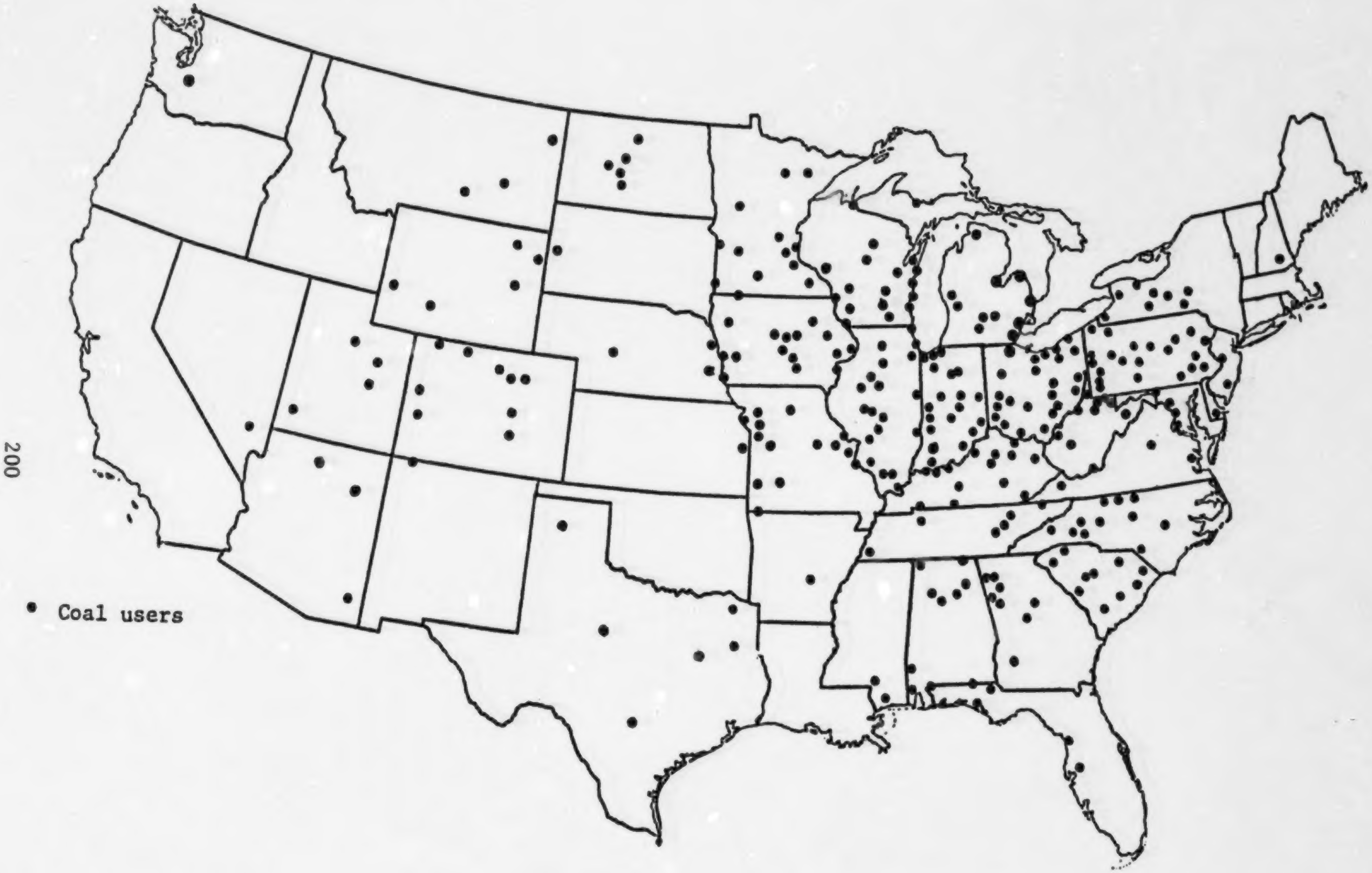

Figure C-2. Location of coal-fired steam-electric power plants.

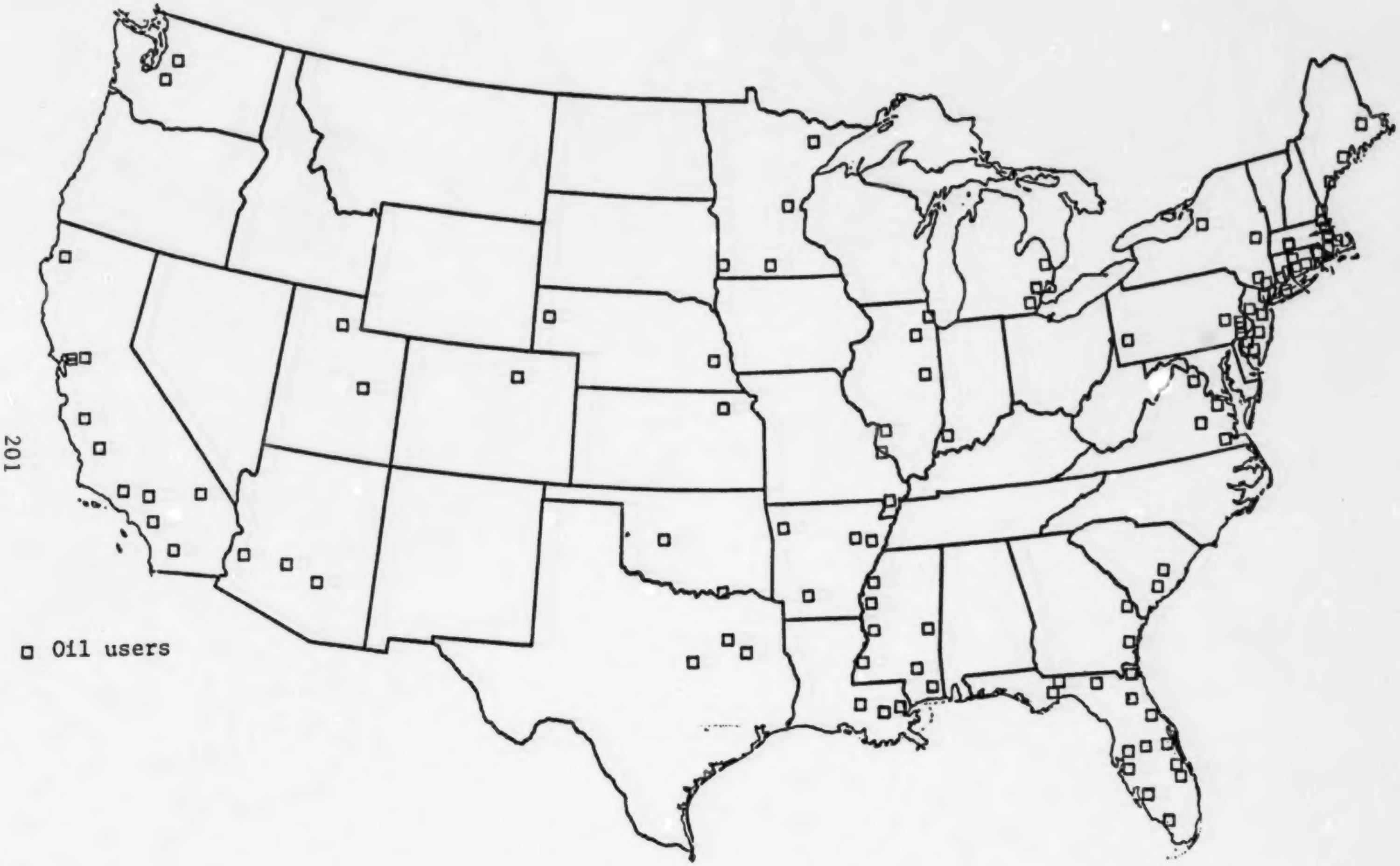

Figure C-3. Location of oil-fired steam-electric power plants.

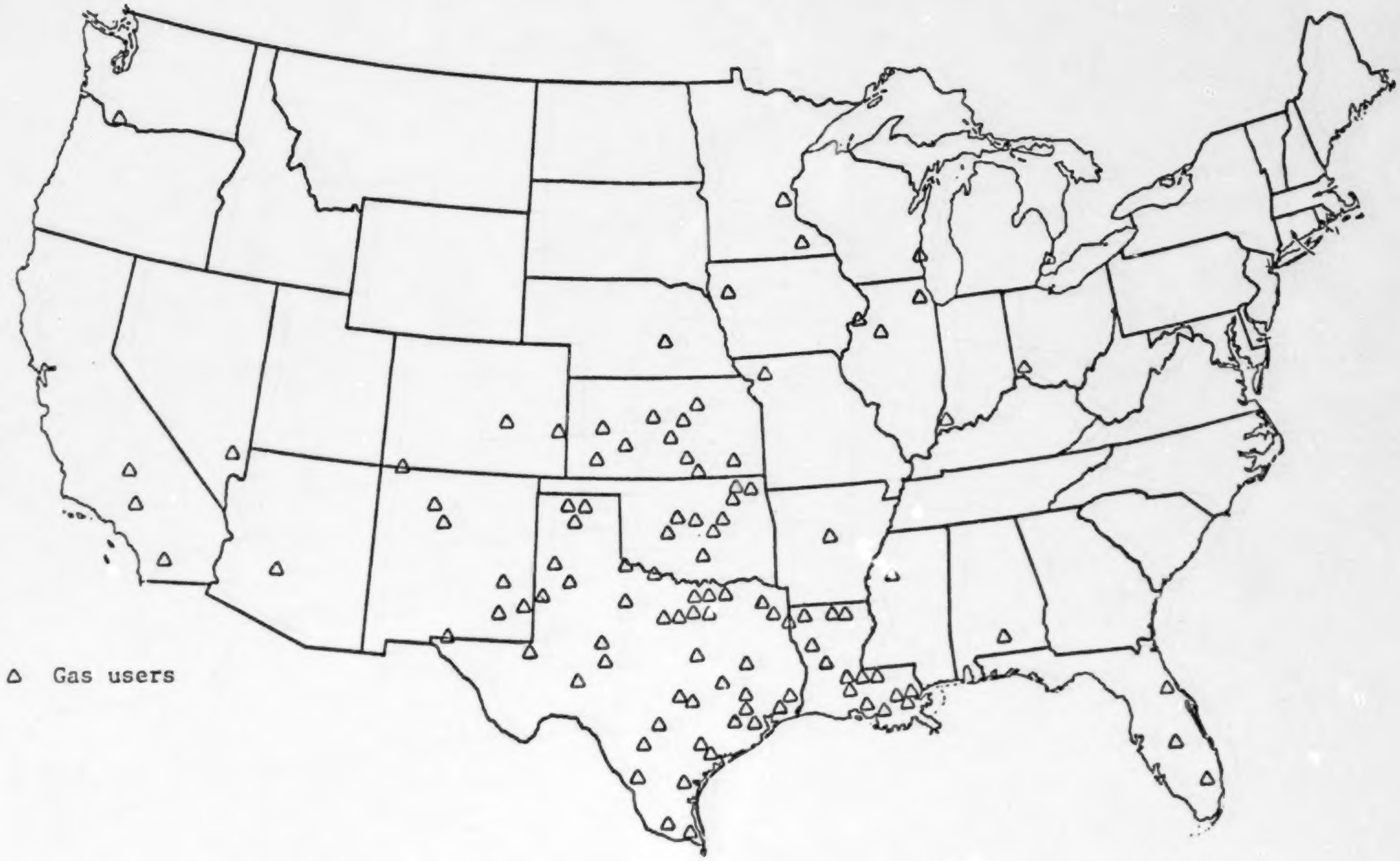

Figure C-4. Location of gas-fired steam-electric power plants.

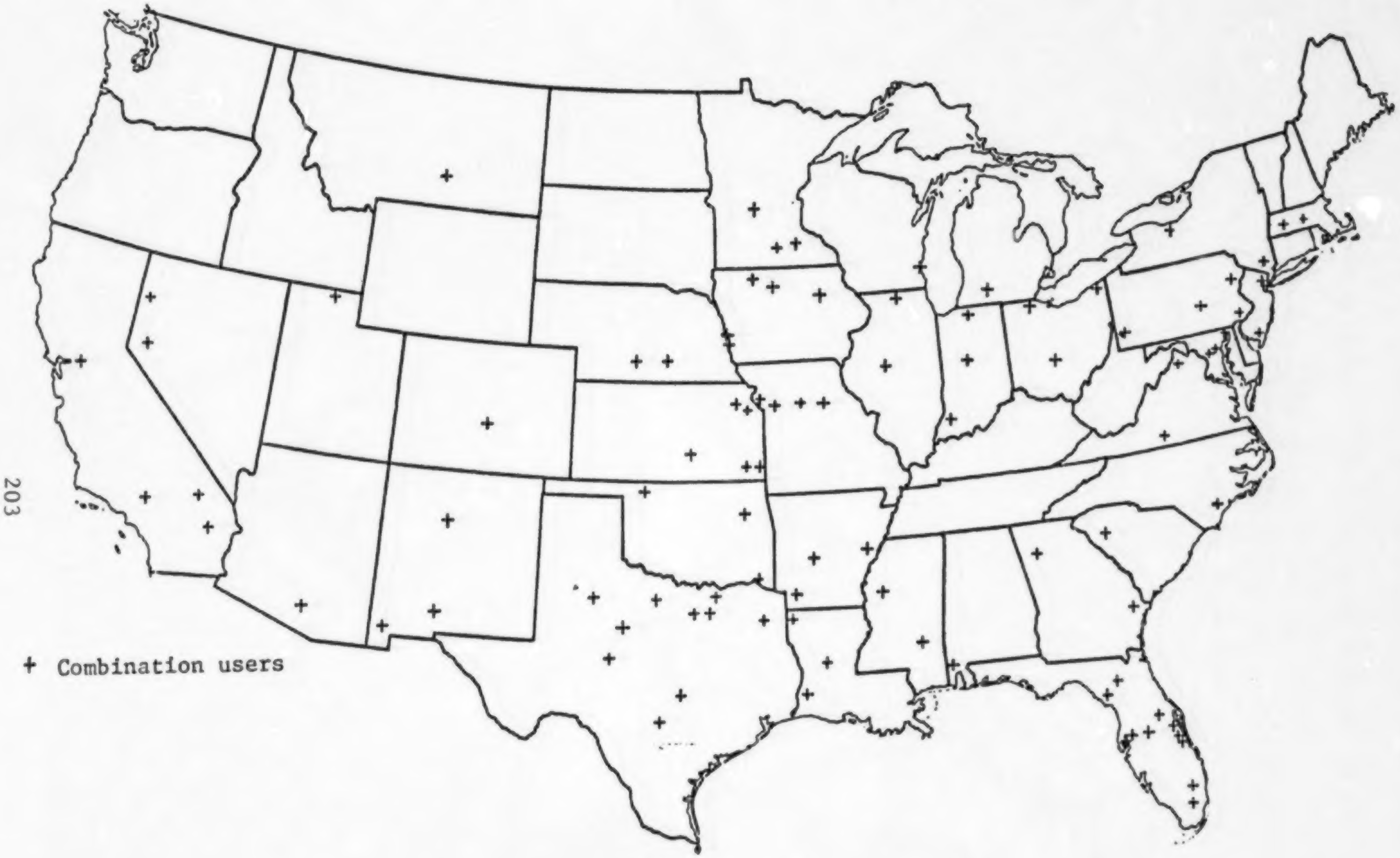
+ Combination users

Figure C-5. Location of steam-electric power plants capable of utilizing alternative fossil fuels.

TABLE C-5. CONVENTIONAL FOSSIL-FUELED STEAM-ELECTRIC GENERATING PLANTS, TOTAL AND AVERAGE CAPACITIES, NET GENERATION AND CAPACITY FACTORS FOR THE TOTAL POWER INDUSTRY, 1938-73[a,b] (1)

	1938	1947	1957	1967	1971	1972	1973
Number of plants	1,165	1,045	1,039	971	985	979	988
Installed capacity, MW	26,066	36,035	99,500	210,237	275,593	294,049	318,357
Average plant size, MW	22	35	96	217	280	300	322
Net generation, GkWh	68.4	174.5	497.2	974.1	1,282.2	1,378.3	1,459.2
Approximate average annual plant factor, %	35	55	57	53	53	54	52

a. Excludes Puerto Rico.
b. Excludes nuclear, geothermal, gas turbine, and internal combustion plants.

BOILER CHARACTERISTICS

Boiler Size

As an illustration of the size relationship between plants and boilers, Table C-6 identifies the total plant size in megawatts and the number of separate units for the 15 largest steam-electric plants in the United States based on 1973 FPC data. These plants range in size from 1872 to 2933 MW. For comparison, individual boiler sizes at these plants range from 69 to 1300 MW. The average boiler size considering all boilers projected to be operational in 1978 is 122 MW and the average boiler size for plants which are projected to be out of compliance in 1978 is 159 MW.

The average size of larger boilers (greater than 300 MW) placed in service has generally increased over the years. Table C-7 shows the number of units, corresponding total megawatts, and the average unit size in megawatts for units placed in service during the period 1959-73.

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1. Federal Power Commission. Steam-Electric Plant Construction Cost and Annual Production Expenses. Twenty-Sixth Annual Supplement-1973, FPC S-250, April 1975. 185 pp.

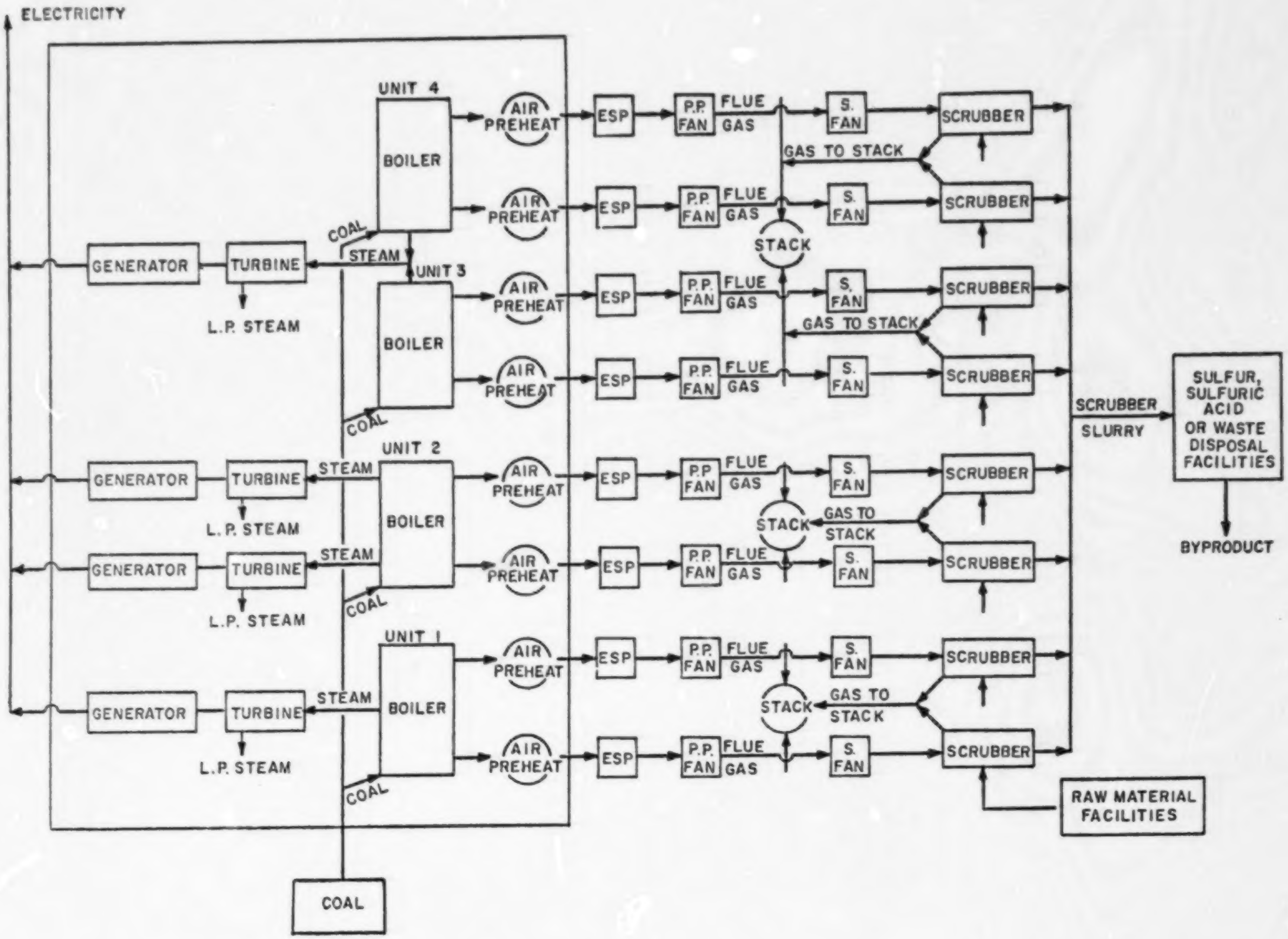
ELECTRICITY
UNIT 4
UNIT 3
UNIT 2
UNIT 1
BOILER
COAL
STEAM
GENERATOR
TURBINE
L.P. STEAM
AIR PREHEAT
ESP
P.P. FAN
FLUE GAS
STACK
S. FAN
GAS TO STACK
SCRUBBER
SCRUBBER SLURRY
SULFUR, SULFURIC ACID OR WASTE DISPOSAL FACILITIES
BYPRODUCT
RAW MATERIAL FACILITIES
COAL

Figure C-6. General layout of a power plant designed with an FGD system.

TABLE C-6. FIFTEEN LARGEST STEAM-ELECTRIC PLANTS IN THE UNITED STATES IN 1973[a] (1)

Plant name	MW[b]	Units	Utility
Amos	2,933	3	Appalachian Power Company
Paradise	2,558	3	Tennessee Valley Authority
Labadie	2,482	4	Union Electric Company
Monroe	2,462	3	Detroit Edison Company
Sammis	2,456	7	Ohio Edison Company
Robinson, P. H.	2,315	4	Houston Lighting and Power Company
Four Corners	2,270	5	Arizona Public Service Company
Moss Landing	2,175	7	Pacific Gas and Electric Company
Alamitos	2,121	6	Southern California Edison Company
Pittsburg	2,029	7	Pacific Gas and Electric Company
Marshall	2,000	4	Duke Power Company
Widows Creek	1,978	8	Tennessee Valley Authority
Nine Mile Point	1,917	5	Louisiana Power and Light Company
St. Clair	1,905	7	Detroit Edison Company
Keystone	1,872	2	Pennsylvania Power and Light Company

a. Coal-fired except as noted.
b. Based on maximum generator ratings.

1. Federal Power Commission. Steam-Electric Plant Construction Cost and Annual Production Expenses. Twenty-Sixth Annual Supplement-1973, FPC S-250, April 1975. 185 pp.

TABLE C-7. TRENDS IN BOILER SIZE, 1959-73 (1)

	Fossil-fueled units 300 MW and larger		
Year	Number units placed in service	Total, MW	Average unit size, MW
1959	5	1,800	360
1960	8	2,525	317
1961	9	3,180	353
1962	7	2,525	361
1963	10	4,500	450
1964	10	3,625	362
1965	17	7,740	455
1966	20[a]	8,424	421
1967	26	13,245	509
1968	22	12,274	558
1969	26	14,249	548
1970	25	14,413	577
1971	29	17,575	606
1972	32	18,753	586
1973	35	21,843	624
Total	281	146,671	522

a. Seven of these units were actually installed in prior years and were rerated in 1966.

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1. Federal Power Commission. Steam-Electric Plant Construction Cost and Annual Production Expenses. Twenty-Sixth Annual Supplement-1973, FPC S-250, April 1975. 185 pp.

Boiler Capacity Factors

The data given in Table C-5 indicate that average annual capacity factors for power plants ranged from about 52 to 57% of rated capacity for the period 1947-73. In contrast, however, capacity factors for individual boilers within a plant vary considerably. As new units are added, load factors for the older units are generally decreased and the newer, more efficient units are operated at higher capacity factors. However, delays in construction of new generating capacity often require older plants to operate at higher than normal capacity factors. Based on historical FPC data for 1967-73, the average annual capacity factors for all boilers as a function of boiler age were determined and are shown in Figure C-7. The data indicate a gradual increase in capacity factors from about 50 to 65% during the first 10 years of operation followed by a relatively constant profile for approximately 5-7 years and a gradually declining operating profile over the remaining life of the plant. Boilers greater than 20 years old generally operate at annual capacity factors less than 50%. A breakdown of the projected 1978 distribution of all boilers by age and capacity factor is shown in Table C-8. Table C-9 shows the distribution for these boilers projected to be out of compliance.

TABLE C-8. DISTRIBUTION OF BOILERS BY AGE AND CAPACITY FACTOR - ALL BOILERS

Boiler age, yr	Number of boilers and (% of total number of boilers)				
	Boiler capacity factor				
	<20%	20-40%	41-60%	>60%	Total
0-5	28 (0.8)	26 (0.8)	84 (2.5)	40 (1.2)	178 (5.3)
6-10	30 (0.9)	34 (1.0)	92 (2.7)	127 (3.8)	283 (8.4)
11-15	20 (0.6)	45 (1.3)	73 (2.2)	120 (3.5)	258 (7.6)
16-30	265 (7.9)	410 (12.1)	465 (13.7)	274 (8.1)	1414 (41.8)
>30	1009 (29.8)	154 (4.6)	61 (1.8)	25 (0.7)	1249 (36.9)
Total	1352 (40.0)	669 (19.8)	775 (22.9)	586 (17.3)	3382 (100.0)

Boiler capacity factors also vary as a function of plant size. Larger boilers are often operated as base-load plants while the older, generally smaller and less efficient boilers are operated to provide peaking capacity. Table C-10 shows a breakdown of the projected 1978 distribution of all boilers by size and capacity factor. Table C-11 shows the distribution for these boilers projected to be out of compliance.

Capacity factors are also a function of fuel type; however, plant design is the primary consideration which affects the consumption-distribution pattern. For plants which are capable of burning alternate fuels, however, the utilization trend changes as a function of fuel availability and costs.

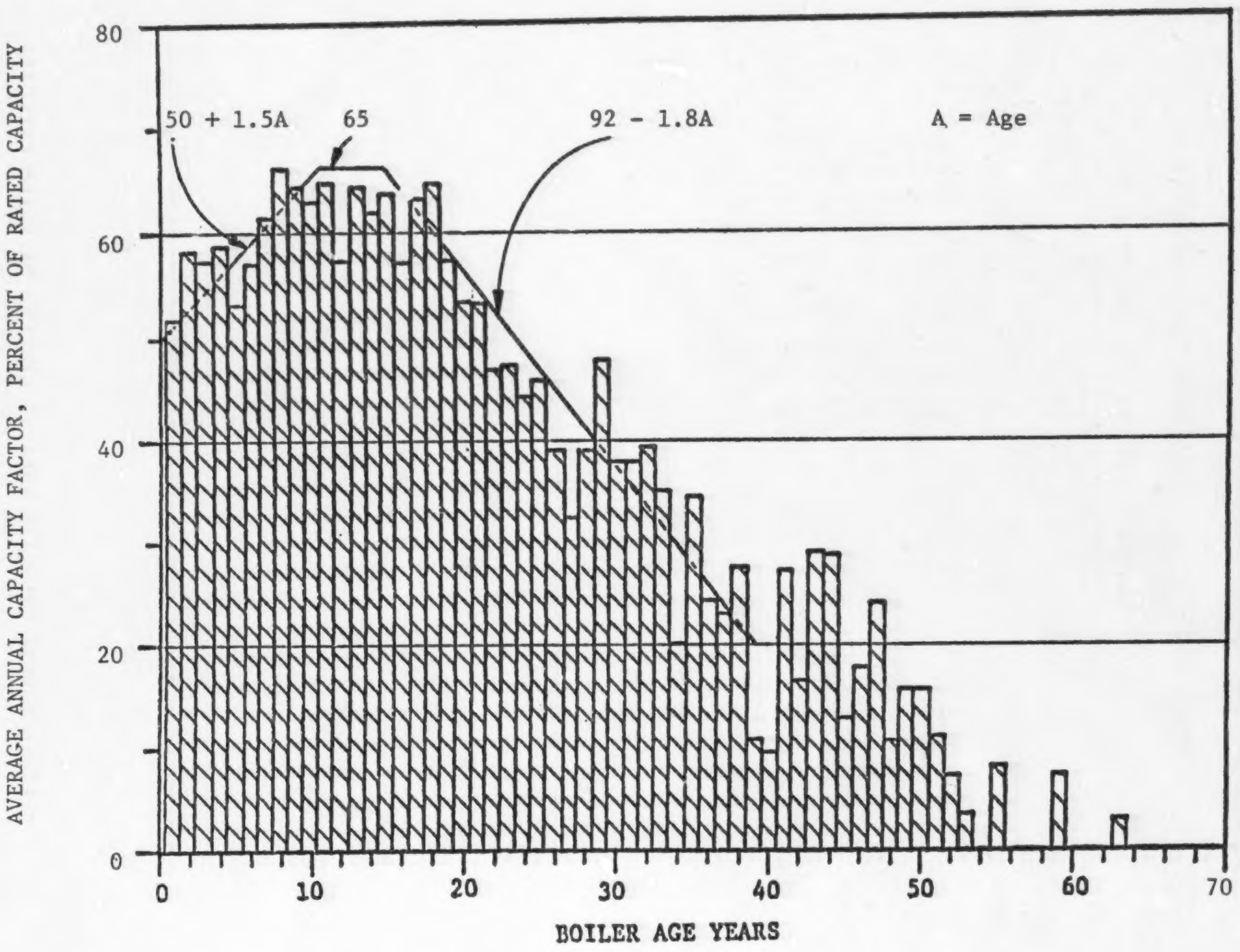

Figure C-7. Average boiler capacity factors as a function of boiler age based on 1969-1973 FPC data.

TABLE C-9. DISTRIBUTION OF BOILERS BY AGE AND CAPACITY FACTOR - BOILERS OUT OF COMPLIANCE

Boiler age, yr	Number of boilers and (% of total number of boilers)				
	Boiler capacity factor				
	<20%	20-40%	41-60%	>60%	Total
0-5	5 (0.6)	8 (1.0)	49 (5.9)	19 (2.3)	81 (9.8)
6-10	9 (1.1)	5 (0.6)	26 (3.1)	45 (5.4)	85 (10.2)
11-15	4 (0.5)	5 (0.6)	16 (1.9)	26 (3.1)	51 (6.1)
16-30	56 (6.7)	90 (10.8)	135 (16.2)	66 (7.9)	347 (41.6)
>30	216 (25.9)	38 (4.6)	13 (1.6)	2 (0.2)	269 (32.3)
Total	290 (34.8)	146 (17.6)	239 (28.7)	158 (18.9)	833 (100.0)

TABLE C-10. DISTRIBUTION OF BOILERS BY SIZE AND CAPACITY FACTOR - ALL BOILERS

Boiler size, MW	Number of boilers and (% of total number of boilers)				
	Boiler capacity factor				
	<20%	20-40%	41-60%	>60%	Total
<200	1270 (37.6)	601 (17.8)	510 (15.1)	390 (11.5)	2771 (82.0)
200-500	53 (1.6)	45 (1.3)	180 (5.3)	120 (3.5)	398 (11.7)
501-1000	29 (0.8)	21 (0.6)	79 (2.3)	76 (2.3)	205 (6.1)
>1000	0 (0.0)	2 (0.1)	6 (0.2)	0 (0.0)	8 (0.2)
Total	1352 (40.0)	669 (19.8)	775 (22.9)	586 (17.3)	3382 (100.0)

TABLE C-11. DISTRIBUTION OF BOILERS BY SIZE AND CAPACITY FACTOR - BOILERS OUT OF COMPLIANCE

	Number of boilers and (% of total number of boilers)				
	Boiler capacity factor				
Boiler size, MW	<20%	20-40%	41-60%	>60%	Total
<200	283 (34.0)	129 (15.5)	129 (15.5)	87 (10.4)	628 (75.4)
200-500	7 (0.8)	12 (1.4)	69 (8.3)	38 (4.6)	126 (15.1)
501-1000	0 (0.0)	5 (0.6)	36 (4.3)	33 (4.0)	74 (8.9)
>1000	0 (0.0)	0 (0.0)	5 (0.6)	0 (0.0)	5 (0.6)
Total	290 (34.8)	146 (17.5)	239 (28.7)	158 (19.0)	833 (100.0)

Boiler Heat Rates

Because heating values of fossil fuels vary over a wide range, the thermal efficiency of fossil-fueled steam-electric power plants is generally expressed in terms of heat rate. Heat rate is defined as the total Btu of heat required to generate 1 kWh of electricity for delivery to the transmission system. These data are reported annually to FPC at the utility, plant, and boiler level. Table C-12 shows historical national average heat rates for fossil-fueled power plants from 1938-73. This table also shows the thermal efficiency for converting heat energy into electricity, which is calculated by dividing the thermal equivalent of 1 kWh (3413 Btu) by the heat rate. As shown, national average heat rates have declined from a high of 16,500 Btu/kWh in 1938 to about 10,400 Btu/kWh in 1972-73.

According to FPC data, there were 14 units in 1973 with heat rates of less than 9 kBtu/kWh compared with 18 units in 1972. The most efficient single unit had a heat rate of 8714 Btu/kWh in 1973. Corresponding to 1973, there was a total of 41 plants with overall heat rates of less than 9,500 Btu/kWh and 124 plants with heat rates under 10,000 Btu/kWh. These totals account for 19 and 45% of the total electrical generation respectively. The most efficient single plant had an average heat rate of 8818 Btu/kWh. Based on projections to 1978, plant heat rates will range from 8,818 to greater than 30,000 Btu/kWh.

The most efficient heat rate at the company level was reported as 9524 Btu/kWh. In 1973 there was a total of 16 utilities with heat rates less than 10 kBtu/kWh.

TABLE C-12. NATIONAL AVERAGE HEAT RATES FOR FOSSIL-FUELED STEAM-ELECTRIC PLANTS - TOTAL ELECTRIC POWER INDUSTRY, 1938-73 (1)

Year	Btu/net kWh	Thermal efficiency,[a] %	Year	Btu/net kWh	Thermal efficiency,[a] %
1938	16,500	20.68	1962	10,558	32.33
1948	15,738	21.69	1963	10,482	32.56
1952	13,361	25.54	1964	10,462	32.62
1953	12,889	26.48	1965	10,453	32.65
1954	12,180	28.02	1966	10,415	32.77
1955	11,699	29.17	1967	10,432	32.72
1956	11,456	29.79	1968	10,398	32.82
1957	11,365	30.03	1969	10,447	32.67
1958	11,085	30.79	1970	10,494	32.52
1959	10,970	31.11	1971	10,478	32.57
1960	10,760	31.72	1972	10,379	32.88
1961	10,650	32.05	1973	10,389	32.85

a. Based on 3,413 Btu as the energy equivalent of 1 kWh.

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1. Federal Power Commission. Steam-Electric Plant Construction Cost and Annual Production Expenses. Twenty-Sixth Annual Supplement-1973, FPC S-250, April 1975. 185 pp.

APPENDIX D

SO_2 EMISSION REGULATIONS AND APPLICATIONS

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APPENDIX D

SO_2 EMISSION REGULATIONS AND APPLICATIONS

With the passage of the Clean Air Acts of 1963, 1967, and 1970, EPA was given the responsibility and authority to regulate and control air pollution in the United States and its territories. Among other responsibilities, the Clean Air Act required EPA to put into effect National Ambient Air Quality Standards (NAAQS) for pollutants which adversely affect public health and welfare, including SO_2, nitrogen dioxide, particulate matter, carbon monoxide, hydrocarbons, and photochemical oxidants.

STATE IMPLEMENTATION PLANS

The Clean Air Act required each state to adopt and submit to EPA an acceptable plan for attaining, maintaining, and enforcing NAAQS in all regions of the state. These State Implementation Plans (SIP) prescribed emission limiting regulations, timetables for compliance with the limitations, and measures required to ensure attainment of the standards. Unacceptable plans were returned to the states for revision or, in some cases, substitute regulations were established by EPA. While the primary responsibility for enforcing SIP regulations rests with the individual states, EPA is responsible for assuring that all implementation plan requirements are fulfilled. As a result, EPA provides technical and legal assistance to the states in enforcing SIP regulations. If any state fails to enforce its implementation plan regulations, the Federal Government may take legal actions against the noncomplying sources.

Following initial approval of most SIP in 1972, many states began submitting to EPA revisions to their implementation plan, many of which alter the emission limitations. Usually, these revisions are based on additional air quality measurement data or on a more detailed technical analysis of air pollution control strategies. When approved by EPA, these revisions become a part of the implementation plan.

FEDERAL NEW SOURCE PERFORMANCE STANDARDS

In addition to the SIP limitations, emissions from certain sources are restricted further by the Federal New Source Performance Standards (NSPS).

The purpose of these standards is to prevent the occurrences of new air pollution problems, encourage improvements in emission control technology, and provide a mechanism for controlling pollutants which EPA suspects are hazardous, but for which insufficient information is available to regulate under other provisions of the Act.

The standards are applicable to newly constructed facilities, new equipment additions to existing facilities, and existing equipment which is modified in such a way that an increase of pollutant emissions occurs. NSPS is in most cases more stringent than SIP.

TRENDS IN ESTABLISHING SIP

Over the past few years, much attention has been focused on emission regulations for sulfur oxides since these regulations impact the supply of fuel, particularly coal, which can be burned to produce electrical energy. While U.S. supplies of coal are plentiful, some of this coal is too high in sulfur content to be burned in compliance with State and Federal regulations for SO_2 without the use of emission reduction systems, which in some cases, are either costly or impractical. As a result, many states have been reevaluating their sulfur oxide regulations to ensure that scarce low-sulfur fuels are being required only in areas where they are needed to protect public health. In some cases, states have revised their sulfur regulations to allow the burning of higher-sulfur fuels in less polluted areas where they can be burned without violating ambient air quality standards.

EMISSION CONTROL REGULATIONS FOR FOSSIL-FIRED POWER GENERATORS

Units of the Regulation

NSPS contains distinct regulations which limit the emission of particulate and SO_2 from individual fossil-fired boilers as shown below.

	Allowable emission, lb/MBtu heat input	
	Coal-fired unit	Oil-fired unit
Particulate	0.1	0.1
SO_2	1.2	0.8

This regulation is applicable to boilers in which construction or modification was begun after August 17, 1971.

In contrast to NSPS regulations, there are variations in (1) the units of measure in which SIP regulations for existing plants are expressed, (2) the equipment (boiler, stack, or entire plant) to which the regulations apply, and (3) the value of the regulation. Table D-1 shows the units in which SIP regulations are expressed (1).

TABLE D-1. UNITS FOR EXPRESSING STATE

SO_2 EMISSION REGULATIONS (1)

1. % sulfur for all fuels.
2. % sulfur for each fuel.
3. lb SO_2/MBtu for all fuels.
4. lb SO_2/MBtu for each fuel.
5. lb sulfur/MBtu for all fuels.
6. lb sulfur/MBtu for each fuel.
7. ppm SO_2 in exhaust gas.
8. Impact on ambient air quality in ppm.
9. lb SO_2/hr.

Some states control all emission sources equally, while other states prescribe different emission limits for sources according to the fuel used, the geographic location, the size of the source, or the type of source (e.g., power plant or other combustion units).

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1. U.S. Environmental Protection Agency. State Implementation Plan Emission Regulations for Sulfur Oxides: Fuel Combustion. EPA-450/2-76-002 (NTIS PB 251 174), March 1976.

The most common regulation for controlling SO_2 emissions is by either limiting the amount of sulfur or SO_2 emitted per unit heat input (pound sulfur/MBtu, pound SO_2/MBtu) or limiting the sulfur content of the fuel (% sulfur). However, other SO_2 regulations limit SO_2 emission concentrations expressed as parts of SO_2 per million parts by volume of stack gas (ppm SO_2) or limit the amount of SO_2 emitted per hour (pound SO_2/hour). Some states or regions specify ambient air quality regulations only (i.e., no specific emission limit for a source). Other methods of limiting SO_2 emissions which appear in the SIP include requiring a percent control of input sulfur (% control) and requiring application of "latest reasonably available control technology" or "new proven technologies."

Some of the above-mentioned methods for regulating SO_2 control the emissions of sulfur oxides more directly than do others, and each method has different implications regarding fuels that can be legally burned.

A detailed discussion of the effect of different applications of the SIP regulations on degree of SO_2 removal is included in State Implementation Plan Emission Regulations for Sulfur Oxides: Fuel Combustion (1).

Application of the Regulations

Besides the various units of measure used, regulations also vary as to the equipment upon which the emission limit is enforced. Twenty-five states or territories enforce their regulations on a boiler basis, 13 on a stack basis, and 18 on a total plant basis (all boilers collectively). In considering compliance with a regulation, this information determines whether a source is allowed to average its emission over all boilers (or stacks) or if each boiler (or stack) must comply with the regulation.

About one-third of the states regulate specific fuel types. These regulations usually control oil-fired sources more strictly than coal-fired sources since, in general, oil contains less sulfur and has a higher heat content than does coal. But, in some cases, the sulfur restriction for coal is more stringent than the restriction for oil to prohibit the use of coal without flue gas cleaning equipment.

About half of the states have specific SO_2 regulations for various geographic areas within the state. These geographic areas might be specified as cities, counties, Federal Air Quality Control Regions (AQCR), Standard Metropolitan Statistical Areas (SMSA), or some locally defined geographic region. In some areas, including Arizona, New Mexico, and Puerto Rico, regulations have been promulgated which apply to specific plants.

1. U.S. Environmental Protection Agency. State Implementation Plan Emission Regulations for Sulfur Oxides: Fuel Combustion. EPA-450/2-76-002 (NTIS PB 251 174), March 1976.

In about one-third of the states, the size of the source determines whether or not the source must comply with an SO_2 emission limitation and if so, the stringency of the limitation. In most cases, source size is defined by the heat input rate measured in millions of Btu per hour (MBtu/hr). Other methods of defining source size include pounds of steam generated per hour (lb steam/hr) and emission potential in tons of SO_2 emitted per year (tons SO_2/yr). In some states, emission limit is determined by the heat input range under which a source falls. In these states, larger sources usually are controlled more stringently than smaller sources.

Over half of the states use more than one of the parameters discussed above in their regulations. In addition, about 35% of the states have separate regulations for new sources and about 10% have regulations for existing sources that become more stringent over time.

In a few states, the limits on emissions or fuel quality are specified as maximum values averaged over a given time period. Most regulations, however, state that emissions or sulfur content shall not exceed a maximum value.

PROCEDURE FOR UTILIZING FPC DATA TO ESTIMATE COMPLIANCE STATUS

Each utility is required by law to report annually to FPC plant, boiler, and fuel characteristics for their steam-electric generators on FPC Form 67. A file containing FPC Form 67 data for the period 1969-73 was supplied to TVA along with utility projections, where available, of similar data for 1978 for use in the byproduct marketing study. The data were primarily for use in projecting SO_2 emissions at power plants for determining the compliance status of power plants with State and Federal SO_2 emission regulations and the market potential for sulfur and sulfuric acid abatement production at plants which are out of compliance.

TVA developed a procedure for using the Form 67 data in conjunction with applicable SO_2 emission regulations to (1) project the compliance status of individual plants and the quantity of sulfur which must be recovered to meet SO_2 emission regulations for those plants out of compliance, (2) estimating costs for removing the required amount of SO_2 from the gas to meet compliance requirements by four alternative scrubbing processes, and (3) comparing the costs for scrubbing including credit from sale of byproducts with alternative costs for complying with the regulation by the use of low-sulfur coal. The overall comparison is used to assist in selecting the minimum cost compliance alternative. Discussions of the data required for input to the scrubbing cost generator and the method for developing the model are given below.

FPC Form 67 Data Projections

The projected 1978 FPC Form 67 data which serve as input to both the SO_2 emission and compliance model and the scrubbing cost generator include a number of key data items which were reported to FPC at the plant level only. In the compliance tests and the scrubbing cost generator the majority of the calculations are begun at the boiler level; therefore, it was necessary to project much of the plant level data to the boiler level for input to these models. Plant level data available from either 1978 projections or historical 1969-73 data updated with more current information from FPC include plant capacity in MW, overall projected plant capacity factor, fuel consumption breakdown as coal, oil, and gas, plant heat rate in Btu/kWh, heating values of coal, oil, and gas, and sulfur contents of coal and oil. At the boiler level, the following data are available from similar sources: boiler startup year, boiler capacity in MW, and design air rates to the boiler at full load expressed in sft^3/minute. Fuel is allocated from the plant level to the boiler level from either utility projections for 1978 or historical 1969-73 consumption. For the cases in which utilities projected plant level data, the data were generally used as projected. For the other cases where historical plant data were used, projections at the boiler level were adjusted in accordance with the historical boiler age-capacity factor relationship which was described earlier. In all cases, data projections and adjustments at the boiler level are allowed to override the plant level data. The projections of fuel consumptions are reported in terms of billion Btu per year (GBtu/yr) for each fuel at each boiler for convenience in comparing the relative fuel distribution, and individual boiler capacity factors (annual) are calculated.

Since individual boiler heat rates are not included in the FPC data file, the overall plant heat rates were assumed to be applicable for each boiler in the plant. Reported air rates to the boiler are compared with calculated air rates as a check of the data file. If reported air rates differ from calculated rates by greater than 25%, calculated air rates are allowed to override the reported rates.

The FPC data file is used by the compliance test model to project SO_2 emissions for each boiler and plant for comparison with allowable emissions. The compliance test procedure is discussed below.

Compliance Test

The SO_2 emission and compliance model uses the projected annual fuel consumption and characteristics data to calculate the annual quantity of sulfur which is emitted for each boiler and plant. For each plant, allowable emissions are calculated based on NSPS for new boilers or the applicable SIP in effect June 30, 1976, for the AQCR in which the plant is located for existing boilers in conjunction with the heating value and sulfur content of the fuel. Excess emissions expressed as tons of sulfur which must be removed per year are then estimated as the difference between the calculated and allowable emissions. In the test for compliance, the plant is considered to be in compliance with the regulation if actual emissions are less than allowable emissions, or do not exceed allowable emissions by more than 10%. This allowance factor is applied to adjust for round-off differences in converting SIP from the various units of expression to the equivalent single unit of expression (lb SO_2/MBtu) for simplification in testing for compliance.

The compliance procedure tests the level of application of the SIP to determine the procedure for complying with the regulation. Levels of application are specified as either (1) an entire plant, (2) an individual boiler, or (3) an individual stack. In all cases where scrubbers are required, they are designed for an SO_2 removal efficiency of 90%. This results in overcompliance for many plants, particularly those which have SIP which apply at the boiler level.

Compliance Procedure for Meeting Plant Level SIP--

When the regulation applies to an entire plant, the model determines the number of boilers which must be scrubbed, ordered from lowest to highest cost, to reduce overall plant emission to comply with the regulation. The FPC data for these plants and specific boilers are used as input to the scrubbing cost generator for projecting costs.

Compliance Procedure for Meeting Boiler Level SIP--

When SIP are applied at the boiler level, the compliance test procedure determines compliance status for individual boilers similar to the method for determining compliance status at the plant level and specifies the boilers which exceed allowable emissions. The FPC data for these plants and specific boilers are then used as input to the scrubbing cost generator for projecting costs similar to the plant level SIP compliance procedure.

A hypothetical example is given to illustrate the difference in SO_2 emission reductions when the two procedures are applied to the same plant. Assume that a plant made up of four equal-size boilers operating at equal capacity factors has a total annual sulfur emission rate of 120 ktons/year and an allowable emission of 60 ktons/year. Excess emissions for this plant calculated by difference are equal to 60 ktons/year. The total sulfur emission rate per boiler is about 30 ktons/year. If scrubbers capable of removing 90% of the sulfur to the boiler were installed on each boiler, the net reduction in emissions for each boiler would be 0.90 x 30k or 27 ktons/year. If the SO_2 emission regulation were a plant level regulation, the reduction in emissions could be achieved by installing scrubbers on three of the four boilers. (Excess emissions = 60 ktons/year; reduction in emissions for three boilers = 3 x 27k or 81 ktons/year, which is greater than the quantity of excess emissions.) If the same hypothetical plant had boiler level rather than plant level SIP, the fourth boiler would not be in compliance, even though the total emissions for the plant were less than the allowable emissions. Therefore, all four boilers would require scrubbers if the regulation were on a boiler basis.

Compliance Procedure for Meeting Stack Level SIP--

Power plants are designed with a wide variety of boiler-stack configurations. Therefore, the application of stack level regulations has different implications as far as the procedure for complying with the regulation. If, for example, the plant is designed with multiple boilers, but with a single stack, the procedure for meeting the regulation is similar to the procedure for complying with plant level regulations. If the plant is designed with separate stacks for each individual boiler, the procedure for meeting the regulations is similar to the procedure for complying with boiler level SIP. Most power plants fit into one of the above two categories. However, there are a number of plants which have multiple boilers which feed to more than one stack. In some cases, the FPC data for these plants do not include sufficient information to determine the specific association between stacks and boilers. Therefore, it is not possible for these plants to use a compliance test to determine status of individual stacks. Because of this problem, and with the concurrence of EPA, all stack level SIP are used similar to boiler level SIP when the association between boilers and stacks cannot be determined.

The final output of the scrubbing cost generator is an identification of all boilers at each plant which must be scrubbed to meet the SO_2 emission regulation.

Compliance Status of Power Plants

Based on the projected data, there are 187 plants which will be out of compliance with either NSPS (new plants) or SIP (existing plants) in 1978. It should be noted that many of the plants shown as out of compliance are likely to be on a compliance schedule with technology that may be different from that projected. Of these, a total of 69 plants are out of compliance based on plant level SIP and 118 based on boiler level SIP. Boiler sizes for plants out of compliance range from as low as 5 to 1150 MW, whereas plant sizes range from 38 to 2558 MW. Boiler ages for these plants range from zero (new plants) to 60 years old. The total annual quantity of emissions from these plants is equivalent to 5,700 ktons of sulfur per year, compared with an allowable emission rate of 3,200 ktons/year. Based on these projections, an average overall SO_2 removal efficiency of 44% would be required to bring these plants into compliance.

The method for using the output of the compliance tests to project costs for meeting the regulation by FGD is discussed in Appendix E.

APPENDIX E

SCRUBBING COST GENERATOR

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APPENDIX E

SCRUBBING COST GENERATOR

DEVELOPMENT OF THE SCRUBBING COST GENERATOR

The purpose of the scrubbing cost generator is to provide a simplified, consistent method for projecting comparative costs for installing FGD systems on the power plants projected to be out of compliance with the regulation. Because of the limited amount of information available for input to the model, the projections are to be treated as general rather than specific in evaluation of the results.

The FPC data projections to 1978 and the output of the compliance test models are inputs to the model. The basis for its development and other relevant information concerning its use are discussed below.

TVA in conjunction with EPA published a report entitled Detailed Cost Estimates for Advanced Effluent Desulfurization Processes (1) which projects the economics of SO_2 control by two throwaway processes (limestone- and lime-slurry scrubbing) and three recovery processes (MgO slurry-regeneration, sodium sulfite/bisulfite solution-SO_2 reduction, and catalytic oxidation). The detailed "base" investment and operating cost projections given in the above report for these processes, and the method illustrated for scaling costs, were coded into a computer model to allow for projection of economics for these processes at other capacities based on using the 1978 FPC data projections discussed above. These projections are being used in a separate study of market potential for sulfur and sulfuric acid. A fourth alternative, limestone scrubbing with oxidation to gypsum, was coded for this study to evaluate the potential for producing and using byproduct gypsum in the construction industry.

The base data incorporated into the program correspond to scrubbing processes designed for 500-MW boilers, both new and existing, which burn 3.5% sulfur coal (dry basis). They are assumed to emit 92% of the sulfur in the coal overhead as SO_2 and are designed to remove 90% of the SO_2. The processes were modified from the initial study to exclude the costs for particulate removal.

1. McGlamery, G. G., R. L. Torstrick, W. J. Broadfoot, J. P. Simpson, L. J. Henson, S. V. Tomlinson, and J. F. Young. Detailed Cost Estimates for Advanced Effluent Desulfurization Processes. TVA Y-90; EPA-600/2-75-006 (NTIS PB 242 541/1WP), January 1975. 418 pp.

Investment Scaling Procedure

Direct Investment Scaling--

A method was established for using the FPC Form 67 data and the compliance test data to project the investment and unit revenue requirements for each power plant out of compliance. Quantities of air and sulfur rates to the boiler for the base case are included in the data base.

Similar data are projected for each boiler which is determined from the compliance test to be out of compliance. Relative capacities are calculated to allow for scaling costs. Flue gas processing equipment and costs are estimated assuming that each boiler must be designed with separate, independent equipment. Absorbent preparation and effluent processing areas, however, are designed with common facilities at the plant level to process the combined quantities of absorbent and effluent from all of the boilers. This "common facility" concept minimizes the investment requirements because designing for installation of single large units rather than multiple small units results in an economy of scale.

The FPC Form 67 data base does not contain data specifying flue gas rates from the boiler to allow for scaling of the gas-processing equipment (scrubbers, fans, reheaters, and duct). Therefore, costs for these areas are scaled on the basis of air rates to the boiler. Sulfur emission rates for each boiler are available from the compliance tests and are totaled for each boiler which requires SO_2 control; the total quantity is then used in scaling sulfur processsing costs.

The general form of the equations for scaling costs for (1) the flue gas processing areas and (2) the absorbent preparation and effluent processing areas are shown as follows.

$$\text{(1)}\quad \begin{array}{l}\text{Flue gas processing}\\ \text{area cost for}\\ \text{individual boiler (I)}\end{array} = \begin{array}{l}\text{Base flue gas}\\ \text{processing area}\\ \text{cost}\end{array} \left[\frac{\text{Design air rate to boiler (I)}}{\text{Design air rate to base boiler}}\right]^{B1}$$

where B1 = scaling exponent for the gas-processing equipment whose costs are being scaled.

Total flue gas processing area costs for the plant are equal to the sum of the flue gas processing area costs for each boiler which requires scrubbers.

(2) $$\text{Absorbent preparation and effluent processing area common facilities cost (entire plant)} = \text{Base absorbent preparation and effluent processing area cost} \left[\frac{\text{Total annual sulfur throughput for all boilers which require scrubbers}}{\text{Total annual sulfur throughput for the base plant}}\right]^{B2}$$

where B2 = scaling exponent for the sulfur processing equipment whose costs are being scaled.

Since the absorbent preparation and effluent processing areas are designed utilizing common facilities for the total throughput, these calculated costs do not need to be summed boiler by boiler.

The total direct investment is calculated as the sum of the total flue gas processing area and the common facilities costs.

Indirect Investment Costs--

Indirect investment costs are estimated as a percentage of the direct costs similar to the method used in the initial study. For simplification in developing the model, however, the indirect cost factors do not vary with plant or boiler size. Table E-1 shows the indirect cost factors which are used in projecting total investment requirements for each of the four processes as a function of plant status (new or existing unit).

Investment Adjustment Factors--

The data base was created to allow the input of other factors for adjusting process investment. A process premise factor is an allowable input to adjust the projected process investment. The adjustment is applied uniformly for all plants. It allows the relativity of process investments to be varied from that reported in the initial study to reflect updated technology and costs and is applied separate from cost indices. For the current study, process premise factors for the limestone and gypsum processes are input as 1.2.

The data base also allows for the use of site-specific factors which can be used for any process and any plant to adjust the investment to take into account special design provisions which were not considered in the initial study. Factors were incorporated for some of the TVA plants to reflect the effect of a common plenum which would require fewer scrubbers, and to adjust for higher projected capacity factors in comparison with projected FPC factors.

TABLE E-1. INDIRECT INVESTMENT AND ALLOWANCE FACTORS (1)

	Indirect investment and allowance factors as a percent of direct capital investment	
	Limestone and gypsum processes	
	New	Existing
Indirect Investment Factors		
Engineering design and supervision	9	10
Construction field expense	11	13
Contractor fees	5	7
Contingency	10	11
Total indirects	35	41
Allowance Factors		
Startup and modifications	8	8
Interest during construction	8	8
Total allowances	16	16

Two additional factors which may be input to the program to impact process investment include (1) a retrofit difficulty factor (developed by PEDCo Environmental, Inc.) and (2) a location factor. Each of these factors is applied specifically to all processes at a given location. The retrofit difficulty factor adjusts the projected investment equally for all processes at a given location to account for site-specific variations in design and layout which would affect costs for installation of each process alternative equally. Location factors are applied in the same manner to account for site-specific differences in construction costs which are related to plant location and terrain.

The FPC data file does not contain information specifying the number of flue gas ducts on existing boilers. Since the number of required scrubbing trains is a function of the number of ducts, power plants with gas flow rates of less than 700 ksft^3/minute were arbitrarily assumed to be designed with two ducts, whereas plants with larger flow rates were assumed to be designed with four ducts.

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1. McGlamery, G. G., R. L. Torstrick, W. J. Broadfoot, T. P. Simpson, L. J. Henson, S. V. Tomlinson, and J. F. Young. Detailed Cost Estimates for Advanced Effluent Desulfurization Processes. TVA Y-90; EPA-600/2-75-006 (NTIS PB 242 541/1WP), January 1975. 418 pp.

Revenue Requirement Scaling Procedure

Direct Costs--

Annual quantities of raw materials and utilities required for each processing area (i.e., absorbent preparation, scrubbing, reheat, byproduct processing, etc.) are identified and are scaled from the base data proportional to the relative gas ratio or the relative sulfur throughput ratio similar to the method for scaling investments. Labor and analyses requirements are scaled proportional to the relative gas or sulfur throughput ratio raised to a fractional exponential power.

Utilities, such as humidification water, reheat, and electricity for the fan, are scaled proportional to the relative gas rate, whereas raw materials and utilities, such as absorbent and electricity for the sulfur-processing areas, are scaled proportional to the relative sulfur rate. Annual costs for raw materials and utilities are then calculated by applying the unit costs to the annual usage rates.

Projected unit costs for labor and utilities for 1978 are shown in Table E-2. Maintenance is estimated as 8% of the subtotal direct investment. Conversion operation costs are defined as the sum of utility, labor, maintenance, and analyses costs. Direct costs are defined as the sum of raw material plus conversion costs.

TABLE E-2. PROJECTED 1978 UNIT COSTS FOR LABOR AND UTILITIES

	Unit cost, $
Labor	
Operating labor	10.00/hr
Analyses	15.00/hr
Utilities	
Fuel oil, No. 6	0.35/gal
Natural gas	2.50/kft^3
Steam (500 psig)	1.40/klb
Process water	0.06/kgal
Electricity	0.027/kWh
Sludge transportation fee (offsite disposal variation)	1.00/ton

The delivered cost of limestone is a major input cost item and is subject to wide variation due to availability and f.o.b. cost of limestone. A 1972 study by the M. W. Kellogg Company (1) estimated delivered cost of high-calcium limestone in 1972 to 37 selected power plants, most of which were located in the eastern half of the United States. Delivered costs ranged from $1.95 to $13.00/ton. Delivered costs were under $4.00/ton to half the plants and all but three in the study could have been supplied at under $6.00/ton. Previous TVA studies had assumed limestone cost at $4.00/ton to each utility. Because of the variability in cost found in the Kellogg study, a limestone data base was developed to use in this and other studies. This data base provides for the calculation of delivered cost of limestone to each utility from the nearest limestone quarry. The f.o.b. price used is the state average price in 1975 plus 10% to reflect 1978 costs. Dolomite sources are excluded from the data base. According to information developed, delivered costs of limestone in 1978 will range from $2.07/ton to $11.23/ton. All but 50 plants in the United States can be supplied at a delivered cost of less than $6.00/ton in 1978.

The data do not assure that limestone is of the quality required for use in scrubbing. Further, there is no assurance that sufficient quantities exist at producing locations to meet long-term utility needs.

The limestone data base was developed from information provided specifically for use in this study by the Bureau of Mines.

A few existing plants do not have adequate land available for onsite disposal of throwaway calcium solids from the limestone slurry process. When this was the case, offsite disposal charges were added. Land cost was assumed the same. Some cost areas were different between onsite and offsite disposal but in sum total investment was approximately equal. Miles to disposal area were added into the cost model and transportation costs were calculated. Costs were based on a charge of $1.00/ton for distances up to 3 miles and then charges were assumed to decline linearly to a minimum of $0.20/ton mile for distances up to 20 miles.

Indirect Costs--

The capital charges included in the indirect operating costs are applied as average capital charges, including depreciation, interim replacements, insurance, and cost of capital and taxes. Depreciation is straight line over the remaining life of the plant (based on an assumed useful life of 30 years). The capital charge allocation for interim replacements varies as a function of the remaining life of the plant.

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1. O'Donnell, J. J., and A. G. Sliger. Availability of Limestones and Dolomites. The M. W. Kellogg Company, Report No. RED-72-1265, February 1, 1972.

For a new plant it is allocated as 0.67% of the total investment, but declines to zero for plants with less than 20 years of remaining life. Insurance is allocated as 0.50% of total investment for all plants. The overall breakdown of capital charges included in the cost projections is shown in Table E-3 (1).

TABLE E-3. ANNUAL CAPITAL CHARGES FOR POWER INDUSTRY FINANCING (1)

	As percentage of original investment		
	Years remaining life		
	30	25	20
Depreciation, straight line (based on years remaining life of power unit)	3.33	4.00	5.00
Interim replacements (equipment having less than 30-year life)	0.67	0.40	-
Insurance	0.50	0.50	0.50
Total rate applied to original investment	4.50	4.90	5.50
	As percentage of outstanding depreciation base[a]		
Cost of capital (capital structure assumed to be 50% debt and 50% equity)			
Bonds at 8% interest	4.00		
Equity at 12% return to stockholder	6.00		
Taxes			
Federal (50% of gross return or same as return on equity)	6.00		
State (national average for states in relation to Federal rates)	4.80		
Total rate applied to depreciation base	20.80[b]		

a. Original investment yet to be recovered or "written off."

b. Applied on an average basis, the total annual percentage of original fixed investment for a plant with 30-year remaining life would be 4.5% + 1.2(20.80%) = 14.90%.

1. McGlamery, G. G., R. L. Torstrick, W. J. Broadfoot, J. P. Simpson, L. J. Henson, S. V. Tomlinson, and J. F. Young. Detailed Cost Estimates for Advanced Effluent Desulfurization Processes. TVA Y-90; EPA-600/2-75-006 (NTIS PB 242 541/1WP), January 1975. 418 pp.

For each process, plant overhead is estimated as 20% of conversion costs and administrative overhead as 10% of operating labor. Administrative overheads in the initial study (1) were calculated on a different basis for processes producing a salable byproduct as compared with sludge-producing processes to take into account the costs for marketing the byproducts. For this study, however, the byproduct prices are assumed to be net prices after marketing expenses have been deducted; therefore, administrative overheads are calculated by the same procedure for each process.

Subtotal indirect costs are defined as the total of capital charges and plant and administrative overheads. Total annual revenue requirements are defined as the total of direct plus indirect costs.

Output of the Scrubbing Cost Generator

The overall output of the scrubbing cost generator includes the following information for each of the four scrubbing alternatives considered.

1. Plant investment
    - $
    - $/kW
2. First-year costs excluding byproduct revenue
    - $
    - Mills/kWh
    - ¢/MBtu
3. Byproduct
    - Production rate, tons/yr
    - Equivalent cost, $/ton
4. Incremental process cost in comparison to limestone scrubbing
    - $
    - $/ton of byproduct

An example output table for an unidentified plant is shown in Table E-4.

The data generated in the scrubbing cost model are used to calculate the scrubbing costs of a throwaway system versus a salable byproduct for each of the 833 boilers identified in this study as operating out of compliance with pollution control laws in 1978.

1. McGlamery, G. G., R. L. Torstrick, W. J. Broadfoot, J. P. Simpson, L. J. Henson, S. V. Tomlinson, and J. F. Young. Detailed Cost Estimates for Advanced Effluent Desulfurization Processes. TVA Y-90; EPA-600/2-75-006 (NTIS PB 242 541/1WP), January 1975. 418 pp.

TABLE E-4. SAMPLE OUTPUT OF SCRUBBING COST GENERATOR

```
                Compliance costs from 1978 projections

Plant code and name
Capacity factor coal   .565   oil    .025
Sulfur content coal    .0320  oil    .0150   gas   0.000
Total capacity  1275.MW    Total boilers 12
      scrubbed  1109.MW                   5


Process                Limestone        Gypsum
Investments
  $                    80152545.        78456732.
  $/kW                      72.3             70.8

First-year costs
Byproduct revenues
excluded
  $                    45078254.        50466002.
  Mills/kWh                 6.82             7.64
  ¢/MBtu                    65.7             73.5

Byproduct                Sludge         CaSO4.2H2O
  Tons/year              426094.          500602.
  Cost, $/ton             105.8            100.8

Incremental costs
in comparison with
limestone process
  $                           0.          5387749.
  $/ton                       0.               11.
```

The alternative fuel costs for fossil fuel power generation are expressed on a common basis (¢/MBtu) for convenience in comparing fuel alternatives.

Clean Fuel Alternative

The "clean fuel" premium alternative is added to provide an option for plants with extremely high projected scrubbing costs. Actual determination of costs to modify plants, purchase, and use clean fuel is not within the scope of the study. Clean fuel premium costs, like scrubbing costs, will vary from plant to plant. For purposes of this study it has been assumed that any plant can purchase and use clean fuel for a premium cost of $0.70/MBtu heat input. For simplicity the clean fuel alternative is assumed constant at all plants.

The clean fuel premium alternative is used in this study as a screening mechanism, but the concept does have usefulness as an indicator of demand for clean fuel. Costs are calculated for each plant out of compliance and are expressed in ¢/MBtu heat input. On a national scale plants which have highest scrubbing costs (those with greatest incentive to use limited quantities of clean fuel) can be identified.